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Innovative Concepts for Detecting and Locating Leaks in Waste Impoundment Liner Systems Acoustic Emission Monitoring and Time Domain Reflectometry

EarthTech Research Corp., Baltimore, MD

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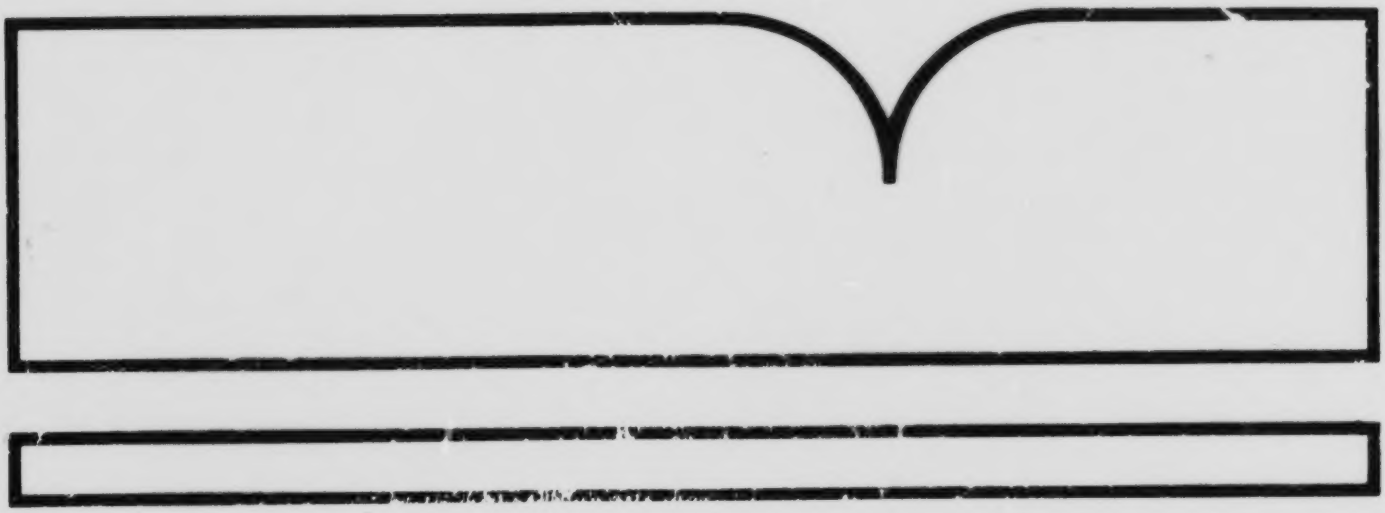

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INNOVATIVE CONCEPTS FOR DETECTING AND LOCATING LEAKS IN WASTE IMPOUNDMENT LINER SYSTEMS

Acoustic Emission Monitoring and Time Domain Reflectometry

by

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Contract No. 68-03-3030

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16. ABSTRACT

This project is part of a program to investigate the use of innovative techniques for detecting and locating leaks in waste impoundment liners. Laboratory and small scale field studies were undertaken to evaluate the potential of Acoustic Emission Monitoring (AEM) and Time Domain Reflectometry (TDR) techniques. Results indicated that both methods do have potential application, but that further evaluations are required to determine usefulness in field conditions.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

Francis T. Mayo
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Laboratory

ABSTRACT

A project was conducted to develop reliable, nondestructive methods for detecting significant leaks in lined waste impoundments before the leachate can seriously damage the ground water. A second goal was to find a technique to locate the precise area where a known leak is occurring. After a preliminary study involving a literature review, a state-of-the-art survey, and a ranking matrix exercise, two techniques were recommended for immediate further study--acoustic emission monitoring (AE) and time-domain reflectometry (TDR). AE monitoring determines the amplitude and frequency responses of sounds emitted when water flows at different rates through soils. TDR is a high-frequency electromagnetic technique that can measure the electrical properties of materials in and around the conductors of a transmission line.

Laboratory and field studies were undertaken to evaluate the potential of these two techniques. Results indicated that AE monitoring potentially offers a practical and inexpensive technique for leak detection and monitoring in both existing and planned liquid waste impoundments. TDR also appears to be a potentially practical method for detecting and determining the position and extent of a leak under a small waste impoundment liner. Further testing is needed to determine the usefulness of both techniques in the field, however.

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CONTENTS

Disclaimer ii
Foreword iii
Abstract iv
Contents v
List of Figures vi
List of Tables viii
Acknowledgments ix

1. Introduction 1
2. Acoustic Emission Monitoring 4
   Introduction 4
   Conclusions 5
   Recommendations 9
   Methods 9
   Results and Discussion 21
3. Time-Domain Reflectometry 41
   Introduction 41
   Conclusions 41
   Recommendations 43
   Methods 44
   Review of Time-Domain Reflectometry Applications in Geologic Materials 45
   Overview of Laboratory Studies 77
   Results and Discussion 81

References 90

FIGURES

Number		Page
1	Schematic diagram of the experimental test arrangement	10
2	The 4-m-long, 30-cm-diameter PVC column used in the laboratory experiments	12
3	Close-up view of the bottom portion of the PVC column	12
4	The reservoir tanks used to store the water for the water flow tests	13
5	Schematic diagram of the plumbing system used in the water flow experiments	13
6	A block diagram of the electronic equipment used to detect the acoustic sounds emitted when water flows through soils	15
7	A photograph of the electronic equipment used to amplify, filter, process and display the acoustic sounds emitted when water flows through soils	16
8	A plot of the grain size distribution of the sand used in these experiments	18
9	An approximate plot of the grain size distribution of the pea gravel used in these experiments	18
10	Plan and cross-sectional views of creep apparatus	19
11	Schematic diagram for a creep apparatus setup	20
12	Sound amplitude at 150 Hz produced when water flows at different rates in the 30 cm diameter tube through 70 cm of sand	23
13	Shows the acoustic amplitude at 300 Hz when water flows through the 30 cm diameter tube at different rates through 70, 100 and 150 cm of sand	23
14	Shows the acoustic amplitude at 150 Hz when water flows through the 30 cm diameter tube at different rates through 70, 100 and 150 cm of sand	24
15	Shows the frequency spectra of sounds produced when water flows at 9, 8 and 6 GPM through 70 cm of sand	24
16	Shows the acoustic amplitude at 200 Hz when water flows through the 30 cm diameter tube at different rates through 70 cm of pea gravel	26
17	Shows the frequency spectra of sound produced when water flows through the 30 cm diameter tube at 10, 8 and 5 GPM through 70 cm of pea gravel	26

Number		Page
18	Shows the acoustic amplitude at 150 Hz when water flows through the 30 cm diameter tube at different rates through 70, 100 and 150 cm of compacted sand. The response from the 70 cm of sand at a density 8% lower than the compacted case is also shown	28
19	Shows the acoustic amplitude at 150 Hz when water flows through the 30 cm diameter tube at different rates through a linear rip of 5 cm and of 15 cm in a 1 mm thick PVC liner material	31
20	Shows the acoustic amplitude of sounds detected when water flows through the system with no soil when the 45 mesh screen is present and when it is removed, and when a window screen is present	31
21	Shows the spectral data from 0 to 500 Hz from a loud-speaker placed in the funnel and the 45 mesh screen is in place and when it is removed	33
22	Shows the spectra from 0 to 500 Hz with the 45 mesh screen only and with compacted sand placed on the screen	33
23	Shows the spectra from 0 to 500 Hz under the same conditions as described in Figure 22 with sand at two densities that differ by 8%	34
24	Shows the spectral response when the microphone is moved 30 cm in a compacted sand	34
25	Shows the water flow rate through the 30 cm diameter tube at different water head levels	35
26	Shows the spectral response from 0 to 500 Hz of the electronic equipment	36
27	Shows the attention of audio signals at 200, 300 and 400 Hz in water as the distance from the loudspeaker to the microphone is varied	38
28	Schematic diagram of the TDR system	43
29	Photograph of the TDR system	46
30	Anomaly placed between the transmission line conductors	46
31	Water content versus dielectric content for mineral soils	49
32	Water content versus dielectric content for glass beads vermiculite and an organic soil	49
33	TDR measured water contents compared with known water content for two different types of transmission lines	51
34	Water content profiles as measured by two types of TDR lines and by gravimetric samplings	53
35	Wetting front versus time as measured by TDR is compared with known wetting front	54
36	Comparison of depth of water added as measured by TDR with that added from the rising water table	54
37	Polarization of the atom of a dielectric by a pair of positive charges	57
38	Real and imaginary part of the dielectric constant for a hypothetical wet material	57
39	Typical relaxation response of the polar water molecule	58

Number		Page
40	A response of the complex dielectric constant versus frequency for a wet soil.	60
41	A comparison of results of K_a versus θ_v from many different experiments	63
42	A general representation of a transmission line	66
43	Types of transmission lines	66
44	The actual dielectric constant response versus the measured dielectric constant of a 300 ohm ribbon type transmission line	69
45	Electric flux density around the conductors of a parallel transmission line	71
46	A block diagram of a TDR system.	73
47	The sampled low frequency output of a repetitive high-frequency input signal	74
48	An idealized TDR data response	74
49	TDR signal responses from a transmission line	82
50	The relative slope of the TDR signal versus the spacing between the conductors of a transmission line	83
51	Plan and side view of the boxes filled with sand between a transmission line	84
52	Five TDR responses from different lengths of boxes between transmission line conductors	85
53	TDR signal travel time versus number of boxes along the transmission line	85
54	Amplitude of the TDR signal response versus the length of boxes along the transmission line	87
55	Amplitude of the TDR signal response versus the length of boxes along the line relative to the conductor spacing	87
56	TDR signal amplitude response versus the width of the anomaly relative to the spacing between the conductors	89
57	TDR signal amplitude response versus length of anomaly along line relative to the conductor spacing with anomaly at different positions along the line	89

TABLE

Number		Page
1	Electrical Properties of Common Geologic Materials	61

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This report was prepared by EarthTech, Inc., under sponsorship of the Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency. The guidance and support of Mr. Carlton Wiles, and the Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency are gratefully acknowledged. The assistance of Dr. Henry Haxo, President of Matrecon, Inc., in problem definition and report organization was invaluable. The diligent and patient efforts of Ms. Sumie Kinoshita, Ms. Patricia Gottal, Ms. Terry Gordon and Mr. Richard Layson of EarthTech Information Services, in technical editing, typing, word processing and drafting are also gratefully acknowledged.

SECTION 1

INTRODUCTION

BACKGROUND

Historically, the ground water in this country has been considered to be too massive to be damaged by man. Over the past decade, it has been increasingly threatened by poor management practices, both in its removal for industrial and agricultural use and by lack of control over waste disposal practices. Contaminants that leak from waste disposal sites percolate into the ground water and eventually into water-supply reservoirs. The Federal Water Pollution Control Act Amendments of 1972 emphasized restoration of the Nation's surface waters. This regulatory action resulted in decreased discharges of waste materials directly into surface waters, but it made the land into a major depository of hazardous waste materials.

Each year about 35 million metric tons of hazardous wastes are put into impoundments lined with natural or manmade materials. The liners act as barriers to the flow of the hazardous wastes between the impoundment site and the ground water. At present, there is little evidence as to the effectiveness of the different liner materials. Furthermore, inadequate techniques are used to monitor the effectiveness of the liner material as a barrier. Currently ground water quality is monitored from wells placed hydrologically down stream. Thus, the waste materials must actually be in the ground water before they are detected and may already have caused significant damage to the ground water. But currently, no methods exist that can determine the source of a leak in a liner before the leachate reaches the ground water.

The purpose of this project was to develop reliable, nondestructive methods for detecting significant leaks in lined impoundments before the leachate can seriously damage the ground water. A second goal was to find a technique that can economically locate the precise area where a known leak is occurring in the liner.

The first step in the project was to identify and evaluate a wide range of techniques for liner leak detection. This step was accomplished by means of a literature review, state-of-the-art survey, and ranking matrix exercise.

LITERATURE REVIEW, STATE-OF-THE-ART SURVEY, AND RANKING MATRIX EXERCISE

Under an earlier contract, EarthTech Research Corporation carried out a thorough literature review, state-of-the-art survey, and ranking matrix exercise evaluating a wide range of techniques that might be applied to leak detection in

waste impoundment liners (Waller and Davis, 1981 [52]). In conducting this review, more than 200 applicable documents were identified and reviewed. Seventy-five documents were actually abstracted and appear in an Appendix to that report. At the conclusion of the state-of-the-art review, a number of techniques were identified, either as having seen actual field application to the leak detection problem at existing waste sites, or as having conceptual application of the problem based on the results of field and laboratory studies in other applications. These techniques or candidates included electrical resistivity, streaming potential, high- and low-frequency electromagnetic techniques such as radar and time-domain reflectometry, and acoustic techniques, including seismic and acoustic emissions.

Finally, a multiple objective ranking matrix was structured for evaluating each of the identified techniques or candidates. A multi-stage procedure was followed to achieve a useful format for the matrix itself and to select and define the parameters used for assessing each candidate. This procedure led to a set of recommendations for applying these various techniques singly and in combination at existing and planned hazardous waste sites. Recommendations were also made for further laboratory and field research into the application of various candidate techniques.

RECOMMENDATIONS OF THE EARLIER STUDY

The earlier study recommended (1) further research into the use of acoustic emission (AE) techniques and pole-dipole resistivity techniques at both existing and planned impoundments, and (2) the application of time-domain reflectometry (TDR) in a grid pattern underlying actual lined impoundments to detect the point source of a leak and to allow for repair before the occurrence of significant environmental damage. Laboratory investigations into the application of AE and TDR to detect liner failings were conducted by EarthTech. This first phase of the technology development is reported here.

DESIGN OF THE PRESENT STUDY

The present report consists of two main sections describing the techniques and the experiments conducted to evaluate them. Section 2, Acoustic Emission Monitoring, deals with experiments to determine the amplitude and frequency responses of sounds emitted when water flows at different rates through soils. Section 3, Time-Domain Reflectometry, examines the geological applications of this high-frequency electromagnetic technique that can measure the electrical properties of materials in and around the conductors of a transmission line. Experiments are discussed that determine the leak size detectable with various spacing of transmission lines.

Section 2 briefly discusses what acoustic emission is and its potential for detecting leaks at waste dump sites. Descriptions are given of the measurement technique used to determine the spectral characteristics of the sounds emitted when water flows through a sand and a pea gravel soil combination and rips in a liner material. Also discussed is the method used to determine the propagation range of the sounds emitted in geological materials. Results of all the experiments are presented and discussed. The results of tests to determine the

quality and significance of our measurements are also discussed. Some conclusions are drawn based on the evidence from our experiments. A number of recommendations are also offered as a guide to future efforts at developing a practical instrument for acoustically monitoring leaks from hazardous waste impoundment sites in a timely manner.

Section 3 reviews the applications of TDR for electrical property measurements in geologic materials. These properties are then discussed, and the principles of TDR are outlined, especially with respect to transmission lines and the TDR equipment. Factors are determined that affect the application of TDR for detecting and determining the extent of an electrical anomaly. Conclusions and recommendations based on our work are offered.

SECTION 2

ACOUSTIC EMISSION MONITORING

INTRODUCTION

Background

Acoustic emission monitoring techniques have been used for at least 50 years to evaluate stresses in rocks and metals, but their application to soil structures is more recent. Acoustic emission techniques have shown potential use in earth stability monitoring, settlement and deformation monitoring, and water flow monitoring through earth dams. The method may also have practical application for monitoring leaks from lined waste impoundments.

Although the mechanism that causes acoustic emissions is not well understood, sound emissions are known to occur from structural distress and from liquid flow through a porous medium (Koerner et al., 1981) [29]. Possibly, soil particles and air bubbles carried by a fluid through a porous medium strike the pore walls and emit acoustic sounds. These sounds can be monitored using a microphone-type device coupled to the ground. Typically in the field, a microphone or undampened accelerometer is coupled to the ground to monitor emissions from an event of interest. Sensors placed on the surface of a site may suffer from poor coupling to the ground and unwanted noise propagated through the air. The attenuation of acoustic signals in geologic materials is not well known. The sensor should be placed physically as near the area of interest as possible.

The literature review carried out by Waller and Davis [52] indicated that the technique has undergone laboratory and field testing and application for several decades. Early applications of AE to measure turbulent flow through earth dams are reported by Esmiol [16] in 1971 for the Bureau of Reclamation; Crook and Coxen [7] successfully applied AE techniques to detect leakage on a dam in Malaysia. In this case, seepage was readily detected along the upstream face of the dam. More recent applications are reported by Koerner, et al., [29], where AE techniques were used to monitor seepage from within boreholes placed along an axis of a leaking earth dam.

AE techniques may have potential application for monitoring waste dumpsites, both to detect seepage and to monitor the movement of a geomembrane liner undergoing stress or failure. Possible rapid attenuation of AE signals through soils and high ambient background noise levels make it a difficult technique to apply at existing sites. But it may be possible to pinpoint a severe leak at an existing solid waste site from a borehole or series of bore holes, and thus actually get close to the point source of the leak. In planned

sites, it may be possible to emplace a grid of transducers beneath the actual landfill liner. Certain acoustic emissions occurring naturally from decomposition of the waste material or settlement and deformation of the impoundment liner may tend to obscure emissions from seepage or liner failures. Liquid impoundment sites offer a better situation for the AE technique. These sites are also potentially much more hazardous if a leak occurs. In any case, AE monitoring would need to take the form of repetitive measurements over long periods of time to establish normal background rates and to identify changes in emission rates over time.

AE monitoring techniques have an established record of field performance, but questions as to the fundamentals of the AE process in soils remain to be answered. These include questions as to the basic mechanism causing the acoustic emissions when liquids flow through soils under both turbulent and laminar conditions, the velocity of fluid flows necessary to cause acoustic emissions, and the propagation effects of acoustic energy in relation to soils. In addition, questions specific to the leak detection problem need to be clarified before AE techniques can be applied optimally in the field. Thus questions as to what magnitude of flows might be expected from leaks and what flows can be heard at what range need further investigation. Answers to these questions will aid in understanding the theoretical aspects of the technique and will thus maximize the application of this monitoring tool.

Objectives

The objectives of the AE phase of this project were to carry out preliminary investigations to answer some specific questions on (1) the spectral characteristics of sound emitted when water flows at different rates through soils, and (2) the range at which the leaks can be detected using acoustic sensors.

The next section discusses the methods used to determine the spectral characteristics of sounds emitted when water flows at different rates through soils and rips in a liner material. The method used to determine the propagation range of the sounds is also discussed.

CONCLUSIONS

Summary

1. Acoustic signals are emitted when water flows turbulently through soils. Signals at frequencies up to 500 Hz are emitted when water flows at rates of 0.3 to 1 cm/sec through sand and pea gravel.

2. The flow must be turbulent for acoustic signals to be emitted. Turbulent flow occurs at rates down to 0.1 cm/sec (1 gpm) in the 30-cm-diameter test column with the sands tested.

3. The acoustic amplitude of the signals increases as the turbulent flow rate increases. For example, at a flow rate of 0.3 cm/sec (4 gpm) through the 30-cm-diameter test column, the amplitude of acoustic signals through

coarse-grained soils is about equal to the background noise at a liquid impoundment site. But at an increased flow rate of 1 cm/sec (10 gpm), the amplitude is 100 times greater.

4. At a flow rate of 0.3 cm/sec (4 gpm), the sound amplitude increases with increasing variation in soil grain size.

5. At a flow rate of 0.3 cm/sec (4 gpm), the sound amplitude decreases with increasing soil density.

6. The sounds emitted when water flows through soils have significant amplitude at frequencies up to 500 Hz, and they have a peak amplitude between 100 and 200 Hz.

7. The attenuation of sounds between 200 and 400 Hz is 10 dB/m near the surface of a lake.

8. No significant sounds were detected when water flowed through either a 5-or 15-cm rip in a 30-mils-thick polyvinyl chloride (PVC) liner material.

Discussion

Detectable sounds are emitted when water flows in a turbulent mode through soils and the amplitude of the sounds decreases as the water flow rate through the soil decreases. No sounds are detected when the flow is laminar. The water flow rates varied from 0.3 to 1 cm/sec (4 to 10 gpm) through a 30-cm-diameter tube over which sounds were measured in the laboratory. At 0.3 cm/sec the amplitude of the sounds emitted as water flowed through soils was generally the same as that of the background noise. In the laboratory, the background noise was two to three times that observed at a lake located in Columbia, Maryland. We believe that the background noise level at this lake would be about the same as that at a waste impoundment pond.

Turbulent flow occurs at rates above 0.3 cm/sec (4 gpm) in the coarse-grained soils tested in this study. No experiments using fine-grained soils such as clays or silts were conducted because the filter system used was unsuitable for fine-grained materials.

It was observed that the sound amplitude increased with the average grain size of the soil. The sound amplitude detected in the pea gravel was about twice that detected in well-graded sand at the same flow rates. The sound amplitude also increased as soil density decreased. Increasing the packing density of the sand decreased the amplitude of the sounds emitted by a factor of 10 at the same flow rates. These results strongly indicate that the shifting of the soil grains with each other is the major source of acoustic sounds in soils.

Turbulent flow in soils is necessary before sounds can be generated. In turbulent flow, the water is flowing in an irregular manner, whereas in laminar flow, the flow pattern is regular and there is no fluid velocity at the pore wall boundary. Under normal conditions in soils, all fluid flow is laminar and no sounds are produced when normal ground water flow occurs in soils. Thus background noise levels from ground water flow will be negligible.

The sounds emitted when water flows through soils have significant amplitudes at frequencies up to 500 Hz. The peak amplitude of the sounds is between 100 and 200 Hz.

The acoustic emissions generated when water flows through soils have been thought to occur at frequencies in the kilohertz ranges [29]. Further indication of this observation is that the commercially available acoustic emission monitoring equipment used had a minimum low frequency cutoff of 100 Hz. This frequency was chosen based on the experience and recommendation of experimenters measuring water flow in soils. Acoustic emissions were detected at a frequency of 6 KHz when water flowed through the sand and coarse gravel filter used at the beginning of the tests. This filter is probably similar to the soil conditions of an earth dam but less typical of the conditions likely to be found under a waste pond liner.

Lower frequency signals, as occurred in the sand/pea gravel tested, offer a significant advantage over higher frequency signals in the kilohertz range because of the lower signal attenuation in soils at these frequencies. The signal propagation range through geologic materials usually increases as the frequency decreases, which is the reason that deep seismic soundings are carried out at frequencies in the hertz range. Soundings carried out in hundreds of hertz range are only useful for shallow (2.5-m-deep) high-resolution measurements. Koerner et al. [29] shows a graph of attenuation versus frequency for iron and steel, rock and coal, and dry sand and clayey silt. The attenuation in the two soils is between 10 and 100 dB/m at 1 KHz. The graph indicates that the attenuation in the dry sand decreases to between 0.1 and 1 dB/m at a frequency of about 100 Hz.

The attenuation measurements carried out in lake water indicate that the attenuation of sounds from 100 to 400 Hz is 10 dB/m. This figure is about 10^7 times greater than the Fink and McKenzie [19] attenuation rate of sounds at 100 Hz in sea water at the surface. These authors mention that there is a relaxation mechanism between 100 and 1,000 Hz in sea water. They also mention that there are other attenuation mechanisms below 50 Hz. Clearly, the attenuation of sounds in water is not simply related to frequency. We feel that much of the acoustic power of our measurements was lost at a water/air interface and that at greater depths, the attenuation of the sound waves would be significantly lower. Further experiments are needed to confirm this hypothesis.

No significant sound amplitude was detected when water flowed through either a 5- or a 15-cm linear rip in 30-mils-thick PVC liner material. Slightly more sound amplitude may be produced with different rip shapes, but acoustic emission amplitudes probably would not increase significantly.

The experiments to determine the amplitude and frequency response of sounds emitted from a creeping liner material were not completed at the time of this report. Further work to characterize the spectrum of these sounds needs to be carried out.

The range at which we can detect water flowing at rates of 0.5 to 1 cm/sec (5 to 10 gpm) in soil is very small indeed (≈1 m) if the sensor is located in water and the attenuation rate is 10 dB/m, as we measured. The range under the above condition increases to about 10 m if the attenuation in water is very low, as expected, and only geometric spreading losses need to be considered. The propagation range of the sound from a leak should be increased if the acoustic sensor is placed in the soil below the liner or in soil on top of the liner. These two situations will also help to reduce the background noise level at the site and thus potentially increase the distance from the leak to the acoustic sensor.

It was found that water flowing in a turbulent mode through coarse-grained soils emits acoustic sounds at frequencies up to 500 Hz. From the attenuation estimates versus frequency in the literature, it was expected that these signals would have a propagation range through geologic materials on the order of 1 to 10 m or more, depending on the flow rate and the background noise level at the site. More site-specific attenuation measurements are necessary.

We now need to consider whether detecting leak rates of more than 0.3 cm/sec (4 gpm) is useful, assuming that we can detect the acoustic signal. First of all, at these flow rates, it is very likely that the level of the containment pond will decrease visibly over a relatively short period of time (i.e., days). Thus a leak of this magnitude will be detected using simple liquid level measuring techniques. Next, the liquid will be removed, and the source of the leak must be determined. But, the location of the leak may not be obvious after the pond has been drained. Sludge on the liner may mask the source of the leak, making this procedure in large ponds a very expensive one in time, labor, and materials. An array of acoustic sensors placed in the pond before and during the leak may be a practical and inexpensive method to determine its source. The distance between the sensors will vary from site to site depending on the background noise level at the site, the water flow rate, and the acoustic properties of the material in the waste pond.

The acoustic monitoring system potentially offers reasonably inexpensive techniques to monitor for leaks and to determine the source of a leak in existing and planned waste impoundment ponds. Further work under controlled conditions is needed to verify the usefulness of the acoustic monitoring technique at a model pond site where leaks can be simulated and controlled. Experiments at such a pond would also help us determine more precisely (1) the range of leak rates that can be detected acoustically and (2) the practical distance from a leak to the sensor in the pond environment. Tests are also necessary at existing liquid waste impoundment ponds to monitor the background noise levels over long periods of time.

RECOMMENDATIONS

The following recommendations are based on the work and results of the experiments discussed here:

1. Determinations should be made as to whether acoustic signals are emitted when water flows through a silt or clay soil.

2. The spectral response of sounds emitted when plastic liner materials creep should be determined.

3. The spectral response should be determined for background sounds emitted at existing waste dumps at frequencies up to 500 Hz.

4. The attenuation of sounds at frequencies from 20 to 500 Hz should be determined in a typical waste impoundment site environment.

5. The advantage of different arrays of acoustic sensors should be established for detecting leaks at waste disposal sites.

6. The spectral characteristics should be determined for acoustic sounds emitted from leaks with known flow rates at a model of a liquid impoundment site.

Fulfilling these recommendations would help determine the usefulness of the acoustic monitoring technique for detecting leaks at waste dumps. These recommendations would also assist in the designing of a practical acoustic monitoring system for detecting leaks at waste dumps.

METHODS

Introduction

The laboratory experiments were designed to determine the amplitude and frequency characteristics of sounds produced when water flows at different rates through different soils. Different heights of soils could be placed in the column and water could be passed through the soils at different known rates. A microphone was placed in the soil and the acoustic signals were amplified, processed and displayed. Special care was exercised to reduce unwanted background noise. A spectrum analyzer capable of capturing transient events was used to process the data. The amplitude and frequency response of the output signal was displayed on an oscilloscope, recorded on a digital tape recorder and plotted on an X-Y plotter. A schematic diagram of the experimental test arrangement appears on Figure 1.

Before discussing the specific methods used to characterize the sounds emitted when water flows at different rates through soils a discussion of the equipment used for the measurements is given. A good deal of the tests carried out were designed to characterize the response of the actual equipment used in the experiments; in other words, a large proportion of the measurements were obtained for quality assurance purposes. The first section describes the test arrangement used for these experiments. The second part of this methods

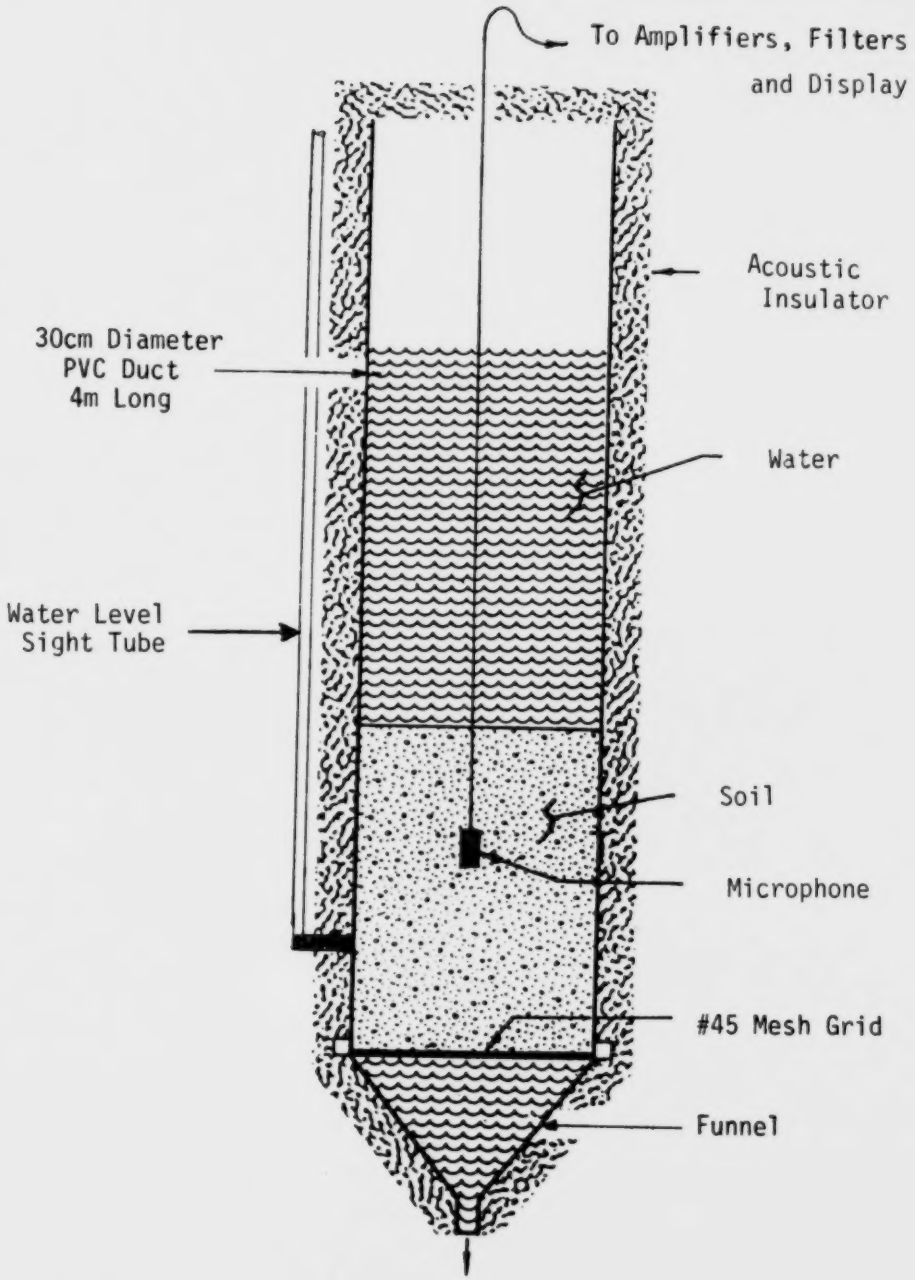

Figure 1. Schematic diagram of the experimental acoustic emission test arrangement.

section describes the electronic equipment used and the third part describes the specific experiments carried out to measure the characteristics of the sounds produced when water flows through soils.

Soil Test Column

A polyvinylchloride (PVC) duct 4 meters long and 30 cm in diameter was available and used to hold the soil column. Figure 2 is a photograph of the experimental test arrangement. Various soils were placed in the column to different heights above a grid mesh and water was allowed to flow through the soil.

The screen used was a 45 mesh (0.4 mm) screen. The screen was supported by flanges in the PVC column as indicated in Figure 3. The mesh size was chosen to stop the soil grains from passing through but allowing as little resistance to the water flow as possible. An additional 1 cm grid mesh screen was placed below the 45 mesh screen to add structural strength since the soil was only supported by the screen.

A funnel was placed below the screen. The funnel effectively reduced the diameter of the water column from 30 cm to 2 cm. Tygon™ tubing with a diameter of 2.5 cm was used for the system plumbing as shown in Figure 4 and schematically in Figure 5. Reservoir tanks were used to store the water that was not in the 4 meter column above the soil as shown in Figure 5. A standard water pump was used to move the water from the reservoir tank into the 4 meter column. A series of open/closed PVC ball valves were used to direct and control the water flow.

The water level in the column was measured by means of a calibrated sight tube placed along the outside of the PVC column. An electronic pressure transducer (gage) was also used so that we would have a record on an X-Y strip chart recorder of the water level above the gage versus time and thus a measure of water flow rate during the experiment. The sight tube also gave an independent means of checking the output of the pressure gage.

A great deal of time and effort was applied to reducing the amplitude of the sounds from all sources other than the water flowing through the soil. The laboratory itself was a significant source of background noise and two methods were used to reduce this noise. First the column was isolated from the concrete laboratory floor by placing the column on 0.2 cubic meter of peat moss. This reduced the background noise from the laboratory by a factor of 10. Soft foam material was wrapped around all of the column and this also reduced the background noise by a factor of about two. All motors and other sources of noise in the laboratory were turned off during the experiments and many of the experiments were carried out over the weekend when there was less noise from adjoining buildings. The Tygon™ tubing also helped to reduce the noise amplitude of water flowing in the plumbing system and to reduce the coupling of unwanted sounds from the laboratory floor.

The second method used to reduce unwanted background noise was by electrically averaging the spectra of the water flowing in the soil. This significantly reduced any transient, non-repetitive noise. An average of the

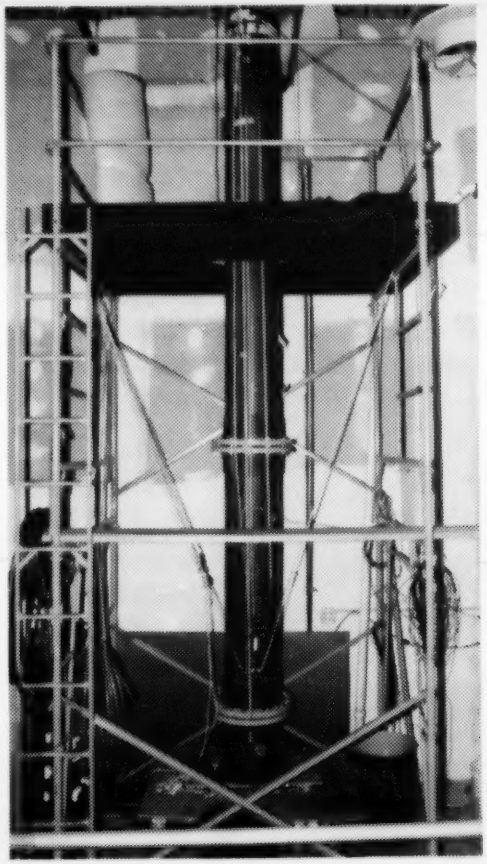

Figure 2. The 4-m-long, 30-cm-diameter PVC column used in the acoustic emission laboratory experiments.

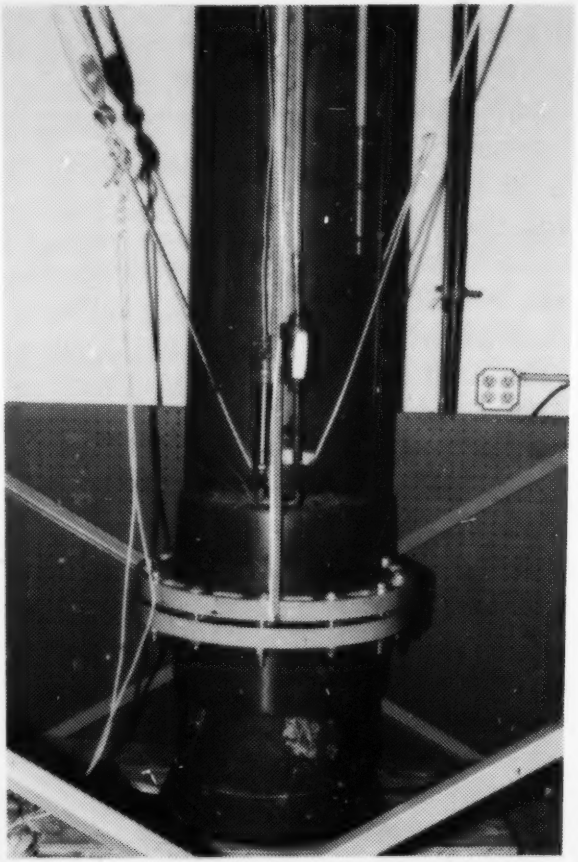

Figure 3. Close-up view of the bottom portion of the PVC column.

Figure 4. The reservoir tanks used to store the water for the water flow tests.

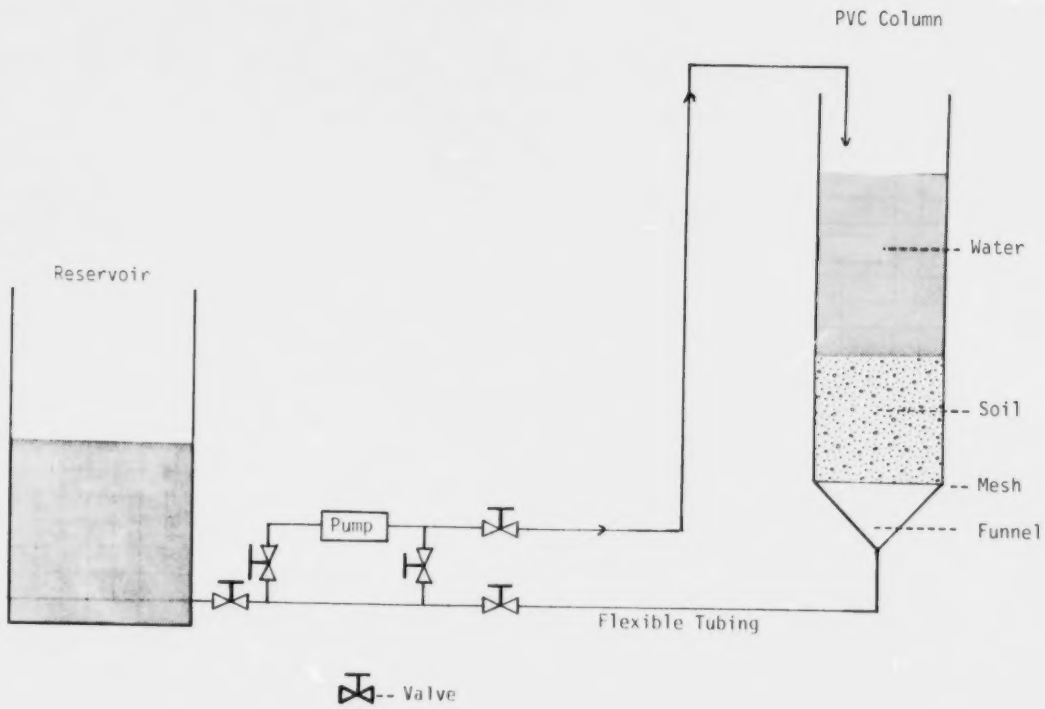

Figure 5. Schematic diagram of the plumbing system used in the water flow experiments.

background noise when the water was not flowing in the soil was taken and subtracted from the response obtained when water was flowing in the soil. Thus, the background noise level from the laboratory was reduced so that the amplitude was only 2 to 5 times greater than the amplitude of the background noise level to the microphone and amplifiers.

Another potential source of unwanted noise was at the screen and funnel. The water flowing in the restricted end of the funnel tended to be turbulent and thus noise was produced. There was no way to reduce the amplitude of the noise at the microphone from the funnel without a major equipment redesign which was deemed uneconomical. Considerable sound damping was achieved by isolating the funnel from the column and using foam between the funnel and the column.

Initially a gravel filter system had been used instead of the screen funnel arrangement. It was soon determined that the gravel filter arrangement produced as much or more acoustic noise when water flowed through the filter than the noise produced when the water flowed through the soils under test; thus the screen and funnel arrangement was designed.

In addition to being acoustically noisy, the gravel filter system used a fiber cloth strainer to stop the sand and soil particles from passing into the plumbing system. After repetitive experiments the cloth clogged up with soil particles. This considerably affected the flow rates and prompted us to consider an alternative system of filter arrangement.

Water flowing through the screen was also a potential noise source. Experiments were carried out to determine the amplitude and frequency spectrum of the noise produced by water flowing through the screen at different flow rates.

Experiments were also carried out to determine the amplitude of the sound reflected or lost at the 45 mesh screen and at the water/soil interface. The procedure used was to simulate the noise source at the mouth of the funnel. This was achieved by placing a loudspeaker at the mouth of the funnel with its diaphragm facing the microphone. The microphone was placed at a position 15 cm above the screen. Then a series of tests were carried out first to determine the sound amplitude with no mesh, then with the mesh installed and finally with 70 cm of saturated soil in the column.

We have discussed the techniques used to improve and measure the acoustic characteristics of the column, its surroundings and the plumbing associated with the column. A discussion of the electronic equipment used to detect, amplify, process and display the acoustic data follows.

Electronic Equipment

The acoustic receiver consisted of a microphone, variable gain amplifiers, and adjustable band-pass filter, a Nicolet spectrum analyzer, a recorder and a X-Y plotter. Figure 6 shows a block diagram of the equipment.

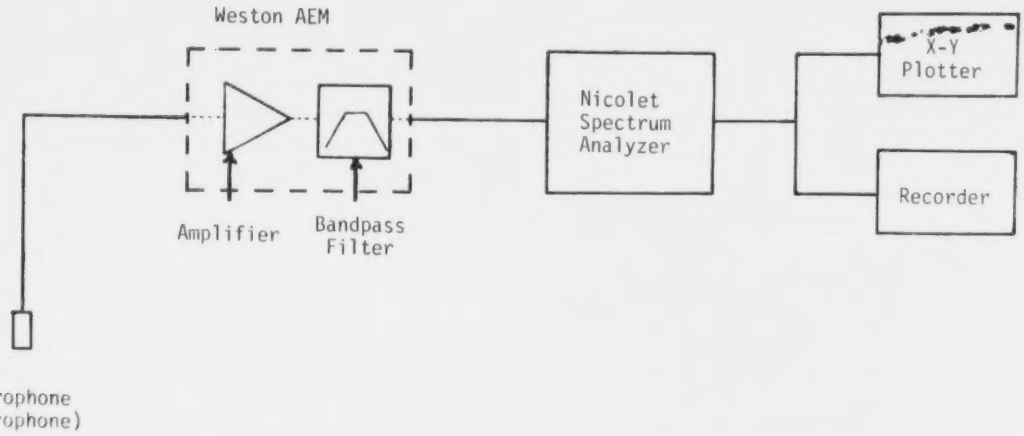

Figure 6. A block diagram of the electronic equipment used to detect acoustic signals emitted when water flows through soils.

The microphone was a piezo-electric sensor. The sensor had a capacitance of 0.018μF and a charge conversion rating of 1.1 x 10^{-8} coulombs/PSI. The microphone produced 6 volts/PSI. The maximum sensitivity of the microphone was 10μV.

The Weston acoustic emission monitor (AEM) used for these tests had a variable gain amplifier of 1 to 5,000. We used the unit at a gain of 5,000 throughout the experiments. The background noise level of the amplifier over a bandwidth of 20 to 1,000 Hz was 0.05 volts. This level was determined by substituting a 0.02μF capacitor for the microphone and measuring the output voltage level of the monitor at a gain of 5,000 and the filter bandpass set at 20 to 1,000 Hz.

The AEM filter unit was modified during the project to cover a frequency range of 20 Hz to 5 KHz rather than the unit's usual bandpass of 200 Hz to 50 KHz. The filters were two-pole, linear-phase, Bessel function analog filters that could be switched.

The amplified and filtered output signals were then fed into a Nicolet 446B mini-ubiquitous spectrum analyzer. The spectrum analyzer digitized the incoming signals and it then carried out a fast Fourier transform on the data. The unit averages up to 512 spectra and stores the data in memory. There were two memories in the unit so that different spectra can be compared with each other. The Nicolet can display the data on a built-in oscilloscope, store the data on a digital cassette tape recorder or put the data out either in analog

or digital form to a plotter. Its frequency range is from 1 Hz to 100 KHz. This unit is a powerful instrument capable of characterizing the amplitude and frequency spectra of transient or repetitive acoustic signals.

Generally all data were plotted on an analog X-Y plotter. All of the data obtained in the field was stored on tape and then the data was later plotted and displayed in the laboratory. The laboratory equipment is shown in Figure 7.

The experiments carried out in the field and some of the laboratory tests used the electronic equipment described above plus a sweep oscillator and a loudspeaker. A Wavetek audio frequency sweep oscillator with a frequency range of 1 to 10^6 Hz was used as the source. A small 2.5 sq cm by 1 cm deep loudspeaker was used to convert the electronic signal to a mechanical signal either in the water or in soils.

The equipment and procedures discussed to this point deal with the measurement technique and the quality assurance of the measurements that were carried out to determine the noise characteristics when water flows through soils. The measurements discussed above were necessary to determine that the amplitude of the acoustic sounds when water flows in the soils were indeed

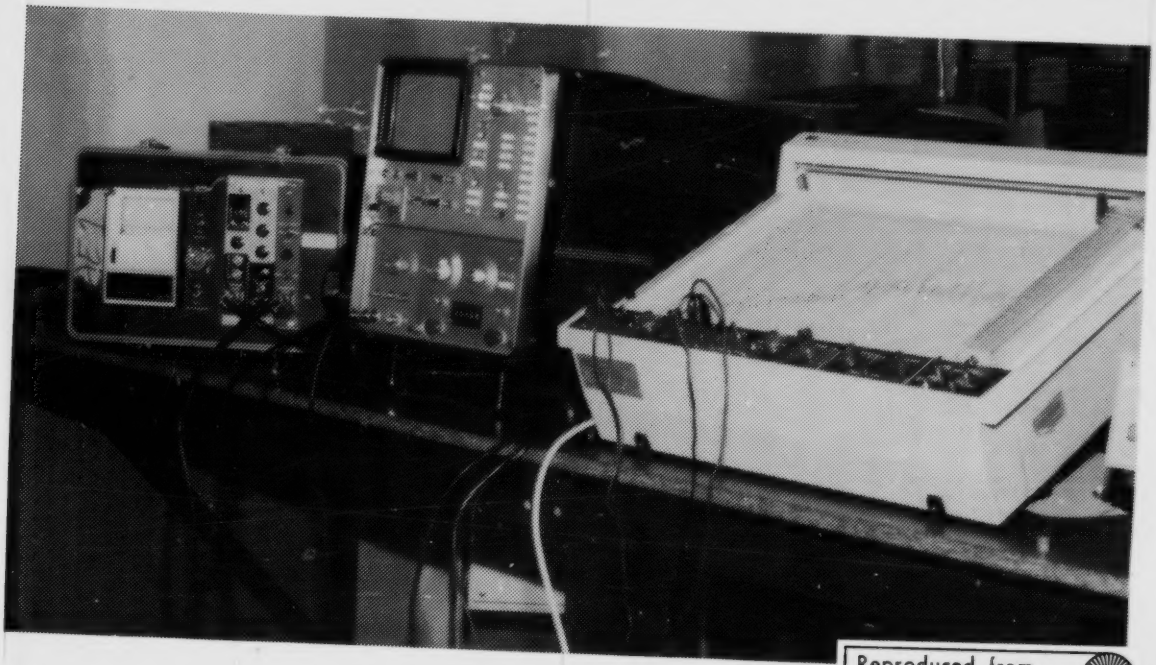

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Figure 7. A photograph of the electronic equipment used to amplify, filter, process and display the acoustic signals emitted when water flows through soils.

significant. A discussion of the methods used to determine the spectral characteristics of the sounds emitted when water flows at different rates in different soils follows.

Measurement Procedure

Generally the method used to carry out the measurements in the laboratory was to place the microphone in the soil under test as shown in Figure 1 and let the water flow through the soil. The flow rate and the acoustic spectra were measured, and the spectral data were plotted on the X-Y recorder. The water level was recorded on an X-time recorder. After about every 30 to 40 cm drop in water level, the flow was stopped and a spectrum of the background noise from within the laboratory was sampled and subtracted from the noise spectra obtained when the water was flowing through the soil.

Soils Tested

The soils used were 20/30 Ottawa sand and pea gravel. The grain size analysis of the sand soil is shown in Figure 8; the average grain size was 0.7 mm. An approximate grain size distribution of the pea gravel is shown in Figure 9; more than 90 percent of the sample fell between 25 and 5 mm, with the remaining portion between 5 mm and 1 mm.

The microphone was placed 15 cm above the bottom of the soil column, i.e., above the 45-mesh screen. Three measurements were taken by adjusting the soil column from 70 cm, to 100 cm and finally to 150 cm.

The equipment and procedures discussed to this point deal with the measurement technique and the quality assurance of the measurements that were carried out to determine the noise characteristics when water flows through soils. The measurements discussed above were necessary to determine that the amplitude of the acoustic signals when water flows in the soils were indeed significant.

The water level varied from about 3 m above the soil to just above the soil in each of the experiments; thus falling water head levels occurred during the experiments. The flow rates typically varied from 1 to 0.3 cm/sec (10 to 3 gpm) in the experiments.

Liner Creep Test

Acoustic emission technique can be used to detect that the liner material is in distress. In case of liner failure, the possible source of microseismic activity could be associated with the elongation of the liner fibers which ultimately results in its failure. Most of the noise produced will be confined to the first phases of the creeping action and will occur a few moments before the material fails.

The experimental setup for conducting a two dimensional creep test for waste impoundment liner fabric is shown in Figure 10. The test fixture consisted of a flange and pressure plate. The circular liner was interposed between

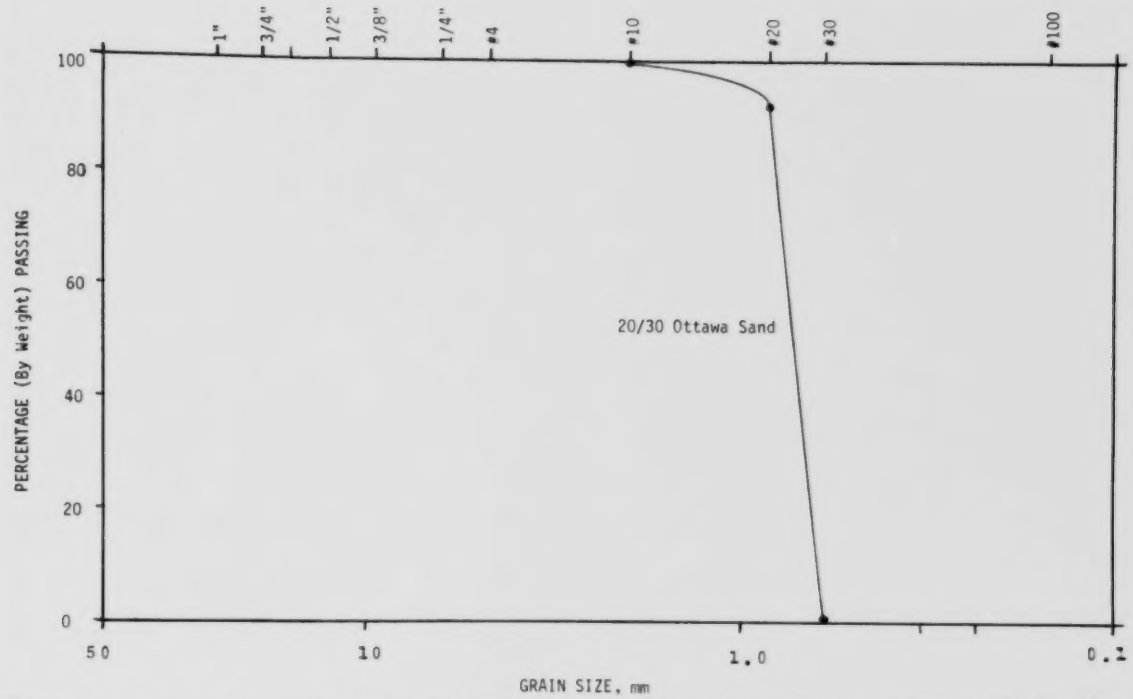


Figure 8. A plot of the grain size distribution of the sand used in the acoustic emission experiments.

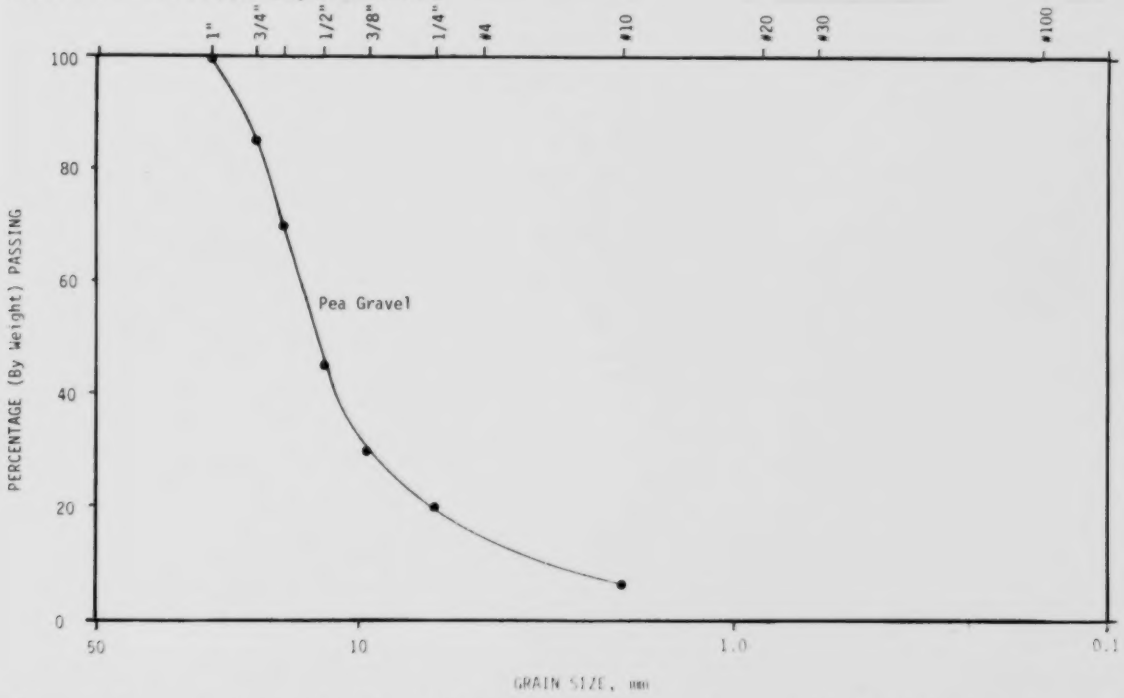
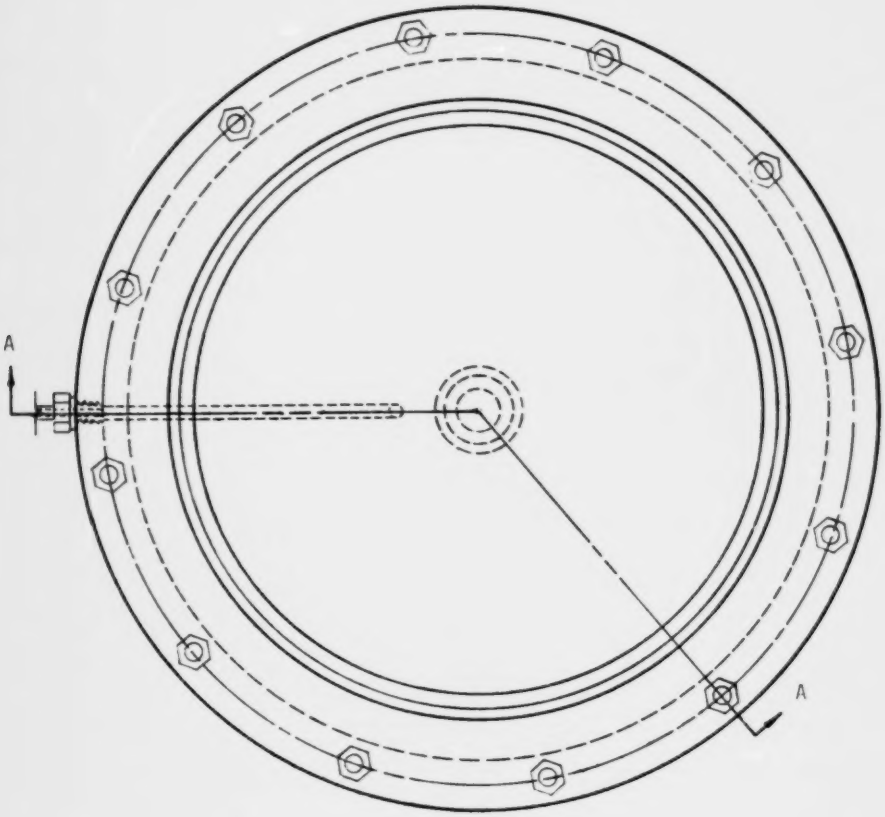
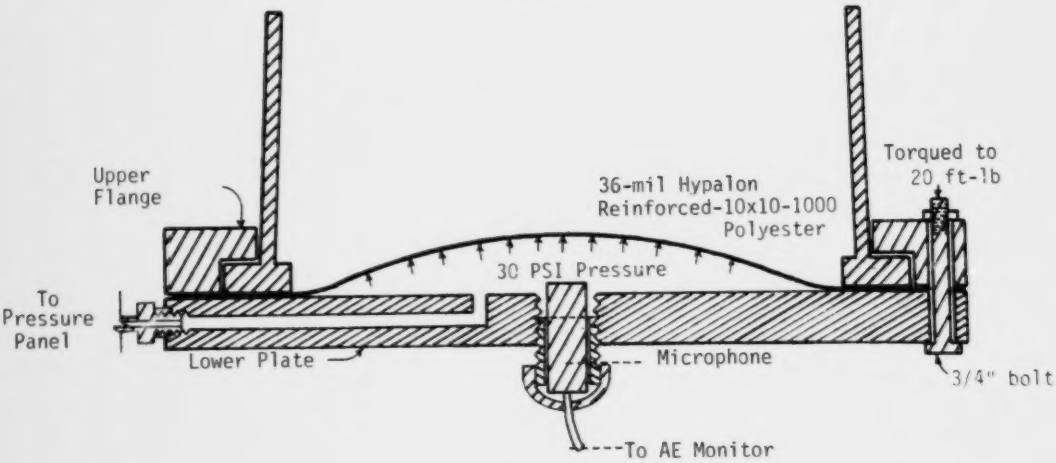


Figure 9. An approximate plot of the grain size distribution of the pea gravel used in the acoustic emission experiments.



PLAN VIEW



SECTION A-A

Figure 10. Plan and cross-sectional views of creep apparatus.

the flange and the pressure plate. To start with, air pressure was applied between the liner and the plate to blow the liner outward. The air pressure of air into the chamber was regulated at the pressure panel.

The apparatus was housed in a wooden chamber. The lid had a 3 cm (2 in) hole in the center of the lid. A dial gage (accuracy 0.001 inch) was placed on the lid. This gage monitored the change in the linear displacement of the liner at the point of its maximum displacement.

To monitor the acoustic signal generated by the liner material in distress, slight modification to the pressure plate was done. A hole 0.5 in. (1.3 cm) diameter was drilled in the center of the pressure plate. The hole was threaded and was used to house the hydrophone (transducer to sense the acoustic signals). Water was forced in between the pressure plate and the liner to blow the liner outward. Water provided a good coupling media between the liner, (the source of signal) and the transducer and permitted a minor loss in the strength of the signal due to dissipation only.

Figure 11 shows the overall schematic overview of the pressure panel and the creep apparatus. The schematic diagram shows how a constant pressure was

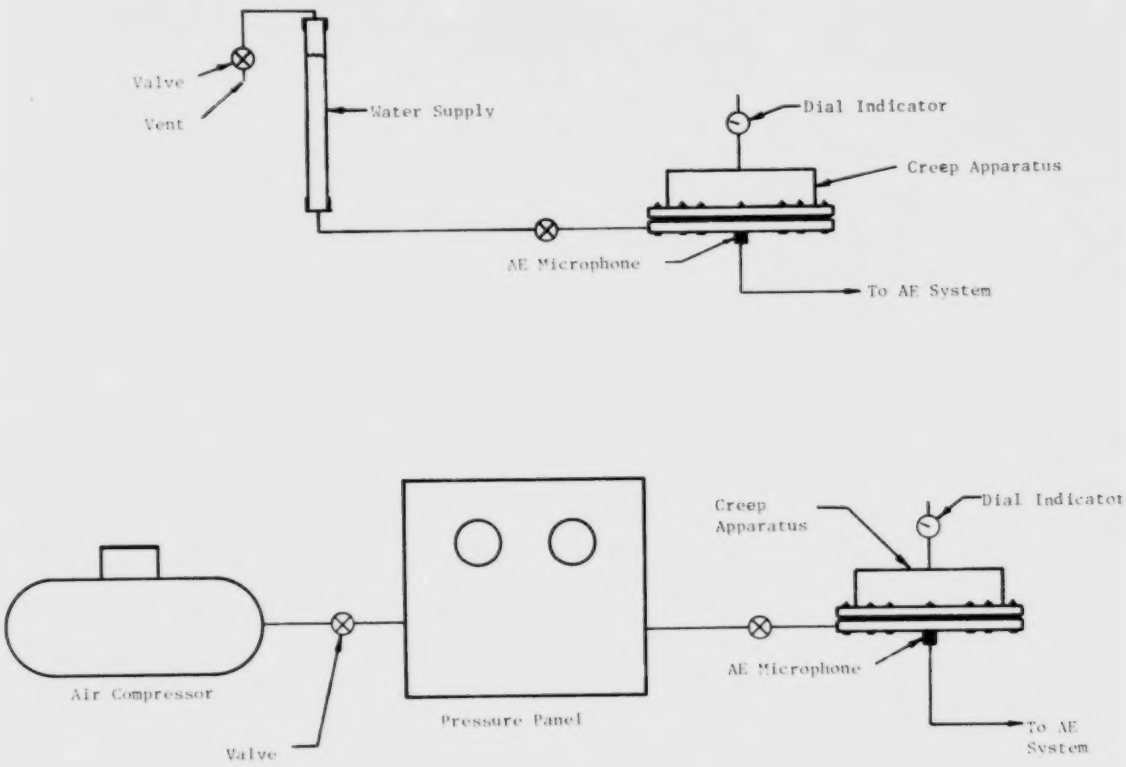


Figure 11. Schematic diagram for a creep apparatus setup.

applied to the liner using the regulators. Figure 10 shows the details in a plan and a cross-sectional view of the creep experiment apparatus.

The objective of the experiment was to monitor acoustic emission when the liner material creeps. In order to do that a study of the creep characteristics of the liner material was necessary. The duration of the creep process is dependent on the initial stress applied to the material. If the stress is too low, little effect is produced. If it is too high, accelerating creep and failure occur too soon. The choice of stress is of considerable importance in case we want to monitor the later phases of the creep process. In order to arrive at the acceptable value of the initial stress that is necessary for the material to creep at an appreciably accepted rate, a series of tests were conducted at different stress levels. The stress levels were selected as a percentage of the failure stress. The failure stress of the material was ascertained from the stress-strain curve supplied by the manufacturer of the liner material.

The series of experiments, done at stress levels of 40 to 50 percent of the failure stress showed that the liner ripped at the contact points between the upper and lower flanges. The rip of the liner occurred due to the fact that large stress concentration were set up at the junction of the upper and lower flanges. Since 70 to 80 percent of the failure stress was needed for a liner to creep at an appreciable rate, the experimental set up was not adequate to handle the above stress levels. The experimental problems did not allow definitive conclusions with respect to monitoring acoustic emission as the liner material creeped.

RESULTS AND DISCUSSION

Introduction

This section presents the results of the experiments carried out--first to determine whether sounds are emitted when water flows through soils, second, to characterize the sounds emitted when water does flow through soils, and third, to determine the attenuation of these sounds in water. We shall begin by showing the spectral data of the sounds emitted when water flows at different rates through soils, and then we shall give evidence and discuss the significance of the data obtained. The results from the field showing the attenuation of the sounds in water will be presented in a similar manner. There were a great number of experiments carried out to determine the significance of the results obtained that pertain specifically to the objectives of the project. These experiments comprised most of the effort in the project and give credence to the experiments relating to the specific objective of the project.

We shall begin by presenting the acoustic data obtained when water was flowing through uncompacted sand, compacted sand, pea gravel and simulated leaks in a liner material. We then show and discuss results of experiments to quantify the noise generated when water flows through the mesh, and the funnel and the reflection of signals from the funnel to the mesh and the water/sand interface. The water flow rates in the empty column are compared with the flow rates when the mesh, the different soils and the ripped liners were added. The frequency characteristics of the electronic equipment is then shown. The

data obtained in the field showing the velocity and attenuation of low frequency audio signals in water is presented and discussed. Finally, a general discussion of the mechanisms causing sound to be produced when water flows through soils is presented.

Laboratory Experiments

Acoustic Amplitude in Sand Versus Flow Rate--

A series of acoustic measurements were carried out on the sand discussed earlier. Figure 12 shows the sound amplitude produced when water flows through 70 cm of sand at different flow rates. The background noise level produced when water flows at different rates through the column containing no soil is also shown.

Figure 12 shows that acoustic signals were produced when water flowed through the sand, and that the amplitude of the sounds decreased as the water flow rate decreased. The sounds produced when the water flowed through the soils decreased to the background noise level at about 0.3 cm/sec (5 gpm).

Background Noise Amplitude--

The major source of the noise produced in the background was from the turbulence of the water in the funnel. The area in which the flowing water was passing decreased from 700 cm^2 to about 4 cm^2 over a length of 25 cm; and thus the velocity of the water increased in the narrow part of the funnel by about 200 times! Part of the noise produced in the narrow part of the funnel was reflected at the water/soil interface and the experiments to determine the decrease in the signal amplitude at this interface are discussed later.

The noise amplitude of the filter system consisting of gravel around a perforated pipe was at least 10 times greater than the funnel system discussed here. The spectrum of the noise emitted from the gravel filter system had signals extending up to 6 KHz at amplitudes 5 to 10 times greater than the background noise levels with no water flowing. The noise spectrum from the funnel system had acoustic signals up to 400 Hz and the amplitudes were only about twice those of the equipment and laboratory noise levels.

The 4-m-long column with the water, soil and air had resonances extending from 25 to 400 Hz. These resonances made absolute noise amplitude measurements very difficult to estimate precisely but all the measurements discussed in this report are compared to one another and thus are only relative. An estimate of the noise levels observed in the laboratory will be related to typical noise levels observed in field situations, and will be discussed later in this section under Field Experiments.

The results of varying the length of sand through which the water is flowing was next examined.

Acoustic Amplitude Through Different Lengths of Sand Versus Flow Rate--

Figure 13 shows the amplitude of sounds produced when water flows through 70 cm, 100 cm and 150 cm of sand. Note that there is a significant variation of noise levels as the length of sand was varied. This result was the

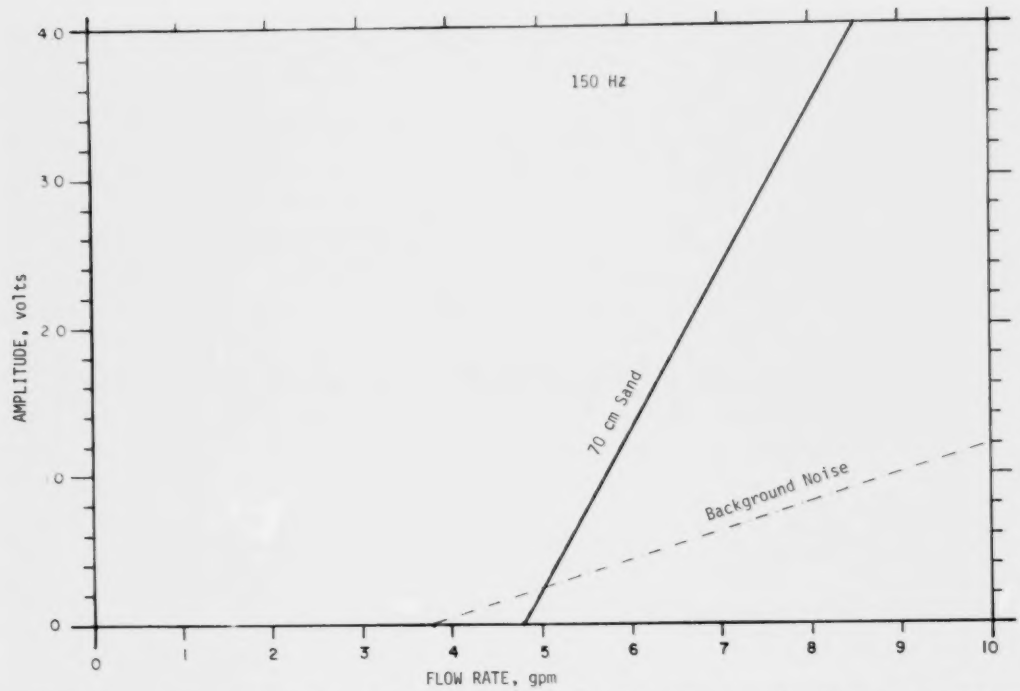


Figure 12. The acoustic amplitude at 150 Hz produced when water flows at different rates in the 30-cm-diameter tube through 70 cm of sand.

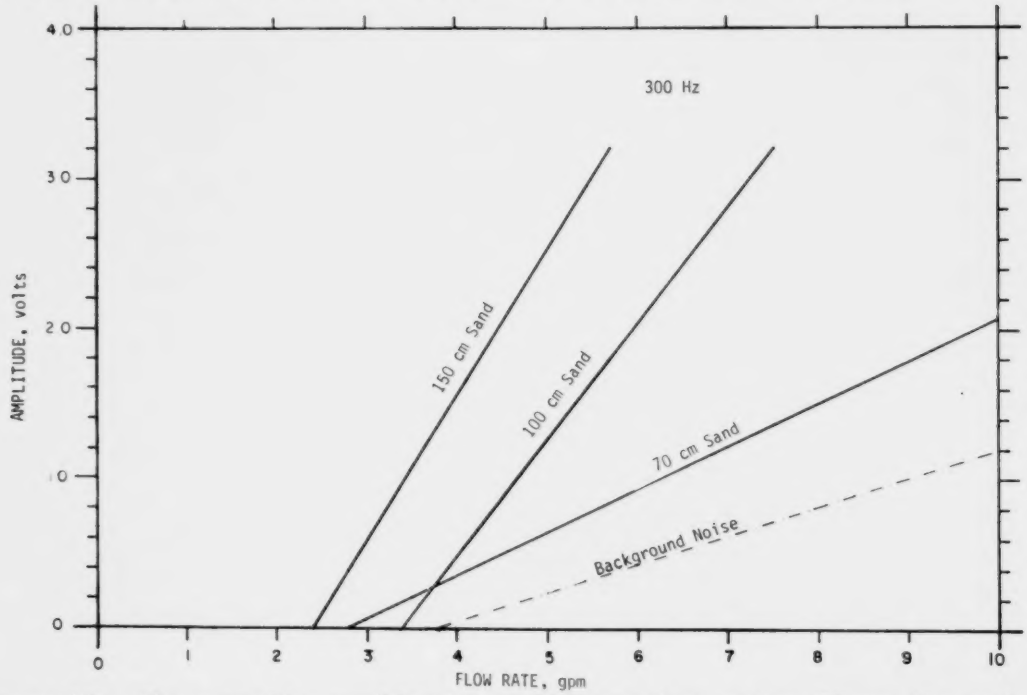


Figure 13. The acoustic amplitude at 300 Hz when water flows through the 30-cm-diameter tube at different rates through 70, 100 and 150 cm of sand.

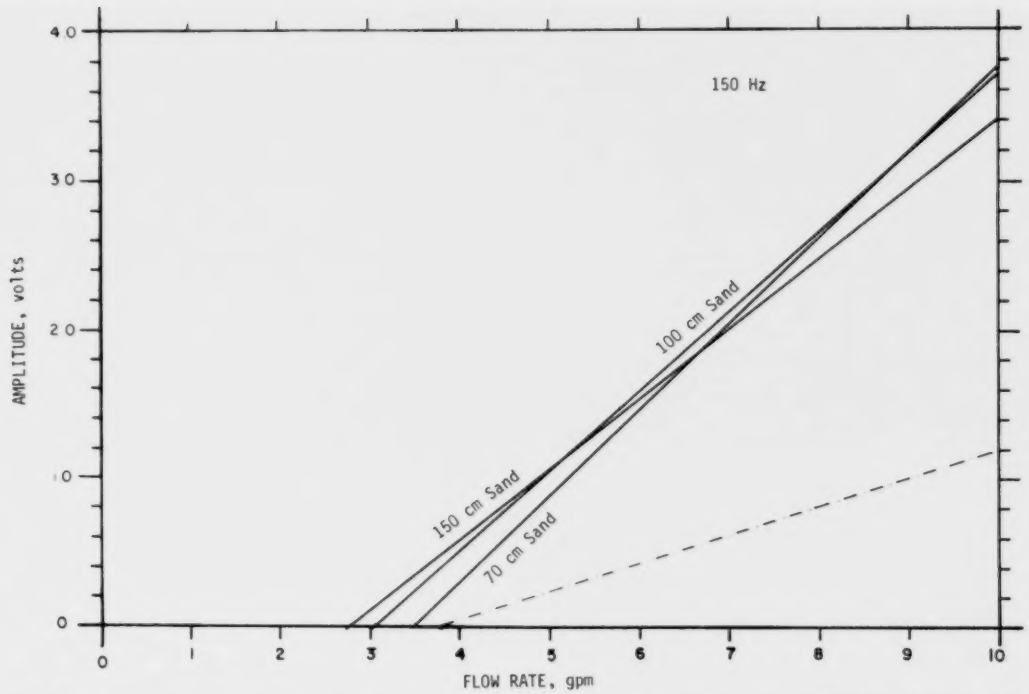


Figure 14. The acoustic amplitude at 150 Hz when water flows through the 30-cm-diameter tube at different rates through 70, 100 and 150 cm of sand.

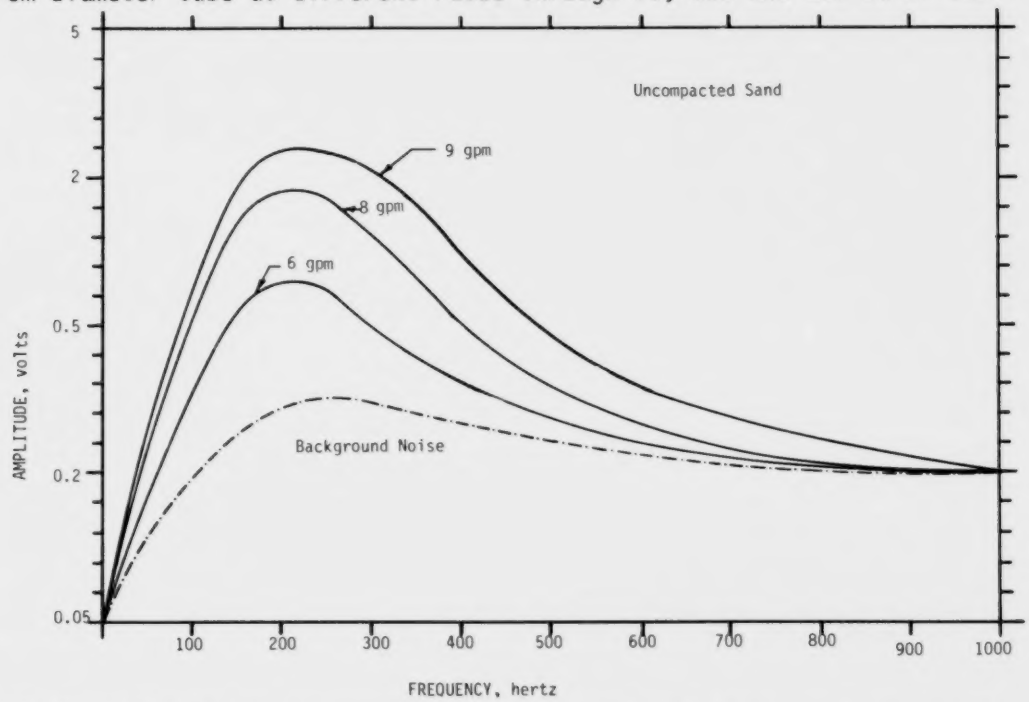


Figure 15. The frequency spectra of sounds produced when water flows at 9, 8 and 6 gpm through 70 cm of sand. The background noise is also shown.

same for all the soils tested at frequencies above 150 Hz. In contrast, Figure 14 shows that amplitude of the sounds emitted below 150 Hz when water flow through different lengths of sand did not vary.

As the number of noise sources increases, i.e. the sand column height increases, the greater the sound amplitude at the microphone. Further, this indicates that the attenuation of sounds was very low at these frequencies. At a frequency of 150 Hz the sound amplitude at the microphone did not vary as water was passed through different column lengths of soil. This was noted for both the sand and the pea gravel. We are not certain why this occurred at a frequency of 150 Hz but it may be that there is a significant increase in attenuations of sounds as the frequency was decreased in the experimental arrangement. Further comment about attenuation of sounds will be discussed after the observations in the field have been presented.

Acoustic Spectra in Sand Versus Flow Rate--

The spectra of sounds produced when water flows at different rates through sand is shown in Figure 15. The background noise spectra is also shown. In this case the water flowed through the 4 meter column with no soil although the 45-mesh screen and the funnel were in place.

The noise spectra at different flow rates was checked periodically to see if there were any frequencies above 500 Hz where the noise level due to water flowing through the soils increased above the noise level of the equipment. No sounds were ever detected at frequencies above 500 Hz.

This is not the same result as Koerner [29] reported in his experiments where he passed water through soils. This discrepancy between the two experiments is not fully resolved at this time. Koerner used a much smaller soil sample holder and thus his system may have had significant resonances at a much higher frequency. The electronic equipment that Koerner used also had a low frequency cutoff at 200 Hz when his data was obtained. The character of all the spectra obtained using the sand and the pea gravel was essentially the same. The peak amplitude varied slightly for different materials as will be shown shortly.

Acoustic Amplitude in Pea Gravel Versus Flow Rate--

Figure 16 shows that the amplitude of the sounds produced when water flows through a 70 cm column of pea gravel. The background level and the amplitude of the sounds produced when water flows through the 70 cm length of sand are shown for comparison.

A significant increase in sound level occurs in the pea gravel compared to the sand soil. The results of the next series of experiments helps to explain the reason for the increased sound levels in the pea gravel compared to those in the sand.

Acoustic Spectra in Pea Gravel Versus Flow Rate--

Figure 17 shows the spectra of the sounds emitted when water flows at different rates through the pea gravel. Note that the character of the response is essentially the same as that of the sand shown in Figure 15. The peak amplitude in the gravel is at 200 Hz rather than 150 Hz in the sand. No

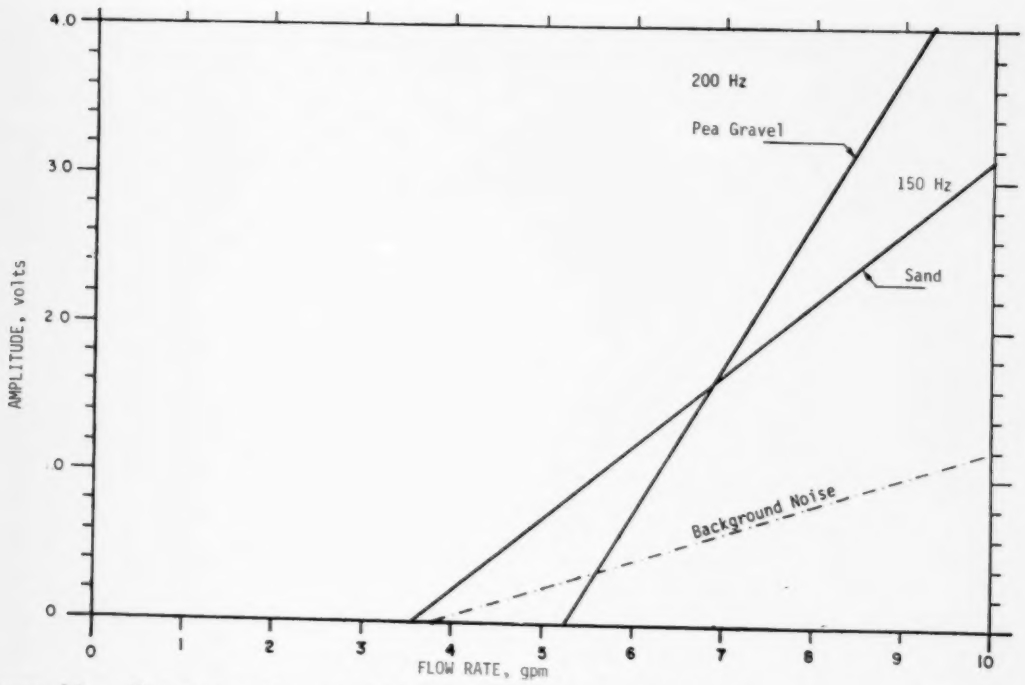


Figure 16. The acoustic amplitude at 200 Hz when water flows through the 30-cm-diameter tube at different rates through 70 cm of pea gravel.

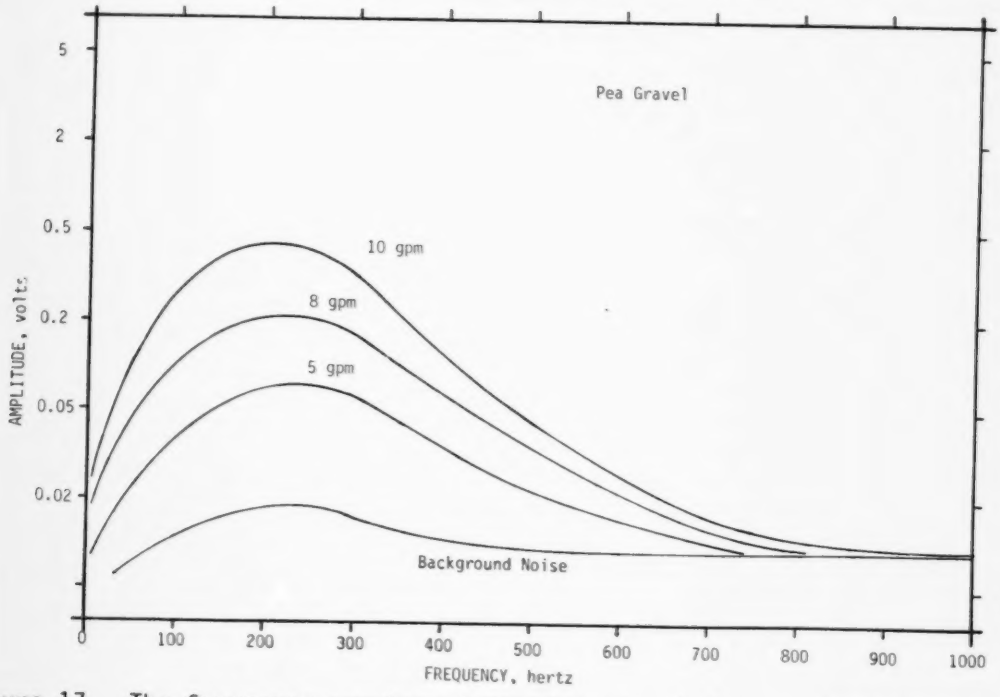


Figure 17. The frequency spectra of sound produced when water flows through the 30-cm-diameter tube at 10, 8 and 5 gpm through 70 cm of pea gravel.

attempt was made in this project to determine why the peak frequency varied in the different materials. Recall that we noted significant sound amplitude was observed at 5 KHz in the gravel filter system used at the beginning of this project. Sand from the column was moving in the gravel filter. The gravel had stones of about 1 to 2 cm^3 on average.

The spectral data for the water flowing through the sand and the gravel indicate that the sound monitoring system should be especially sensitive to frequencies below 500 Hz. Reducing the bandwidth of the amplifiers would help to reduce the amplitude of the background noise level, especially the noise generated in the front end amplifiers. The noise voltage, E, is related to the bandwidth, B, the front end input impedance, R, and the temperature, T, in degrees Kelvin by the following relationship

$$E^2 = 4RKTB$$

where K is Boltzmann's constant equal to 1.4×10^{-23} joules/degree Kelvin. Thus, if the temperature and the impedance at the front end of the amplifier cannot be varied then the bandwidth of the amplifier should be reduced. In this case the bandwidth can be reduced from 50 KHz to 500 Hz, and thus the input noise level reduced by 10.

Experience with seismic sounding would indicate that the attenuation of signals in soils increases with frequency so that the soil itself acts as a low pass filter. The problem is that unwanted geological sounds will propagate from great distances at these low frequencies also, thus increasing the ambient background noise level.

In all of the sand experiments discussed to this point the water was put into the 4-m column from the bottom through the sand. This procedure was used because it was the most practical. A number of experiments in the sand soil where the water was inserted from the top of the volume via a hose were carried out. It was noted that about five cycles of running water through the sand from top to bottom were necessary before the spectral results were repeatable. It was further noticed that the height of the sand column decreased by 8 percent and thus the bulk density of the sand increased by 8 percent. Note that all the pea gravel experiments were carried out by adding water to the top of the column only and waiting for the spectra to be repeatable before the spectral measurements were carried out.

Acoustic Amplitude in Compacted Sand Versus Flow Rate--

Figure 18 shows the amplitude of sounds produced when water flowed at different rates through 70 and 150 cm of compacted sand. The amplitude of the sounds produced was only slightly greater than the background noise level. In other words there was a significant decrease in the amplitude of the sounds produced when water passed through a compacted sand compared to when water passed through an uncompacted sand. This result leads us to believe that the movement of the soil grains with respect to each other is a major source of noise.

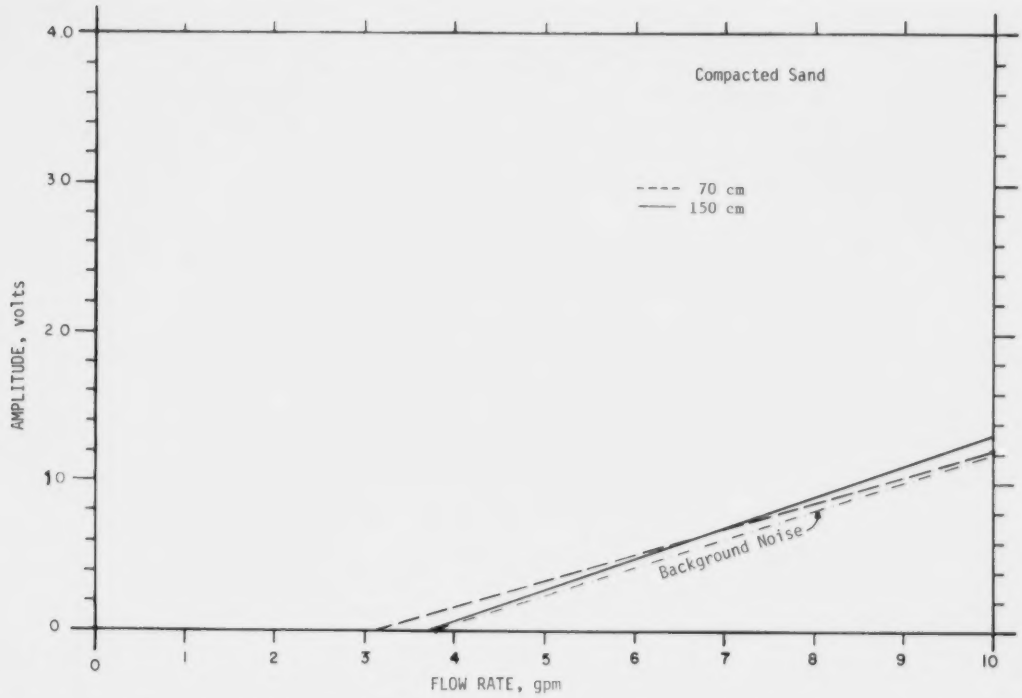


Figure 18. The acoustic amplitude at 150 Hz when water flows through the 30-cm-diameter tube at different rates through 70, 100 and 150 cm of compacted sand. The response from the 70 cm of sand at a density 8 percent lower than the compacted case is also shown.

Source of Acoustic Sounds--

The significant noise amplitude observed when water passes through the pea gravel which has a wide variation of grain sizes also points to the above conclusion that the grains hitting each other is the major source of acoustic sounds. It seems likely that the finer grain particles are moving through the pore spaces set up by the larger grain particles. Recall that we observed significant sound amplitudes when we used gravel as the filter system for the column at the start of this project. In this case the sand grains would move down through the large gravel rocks as the water flowed through the system. Koerner [29] also observed an increase in acoustic emission count rate at the same flow rate when he used turbid water rather than clear water.

A further implication of this observation is that the water flow must be turbulent rather than laminar. In true laminar flow the velocity is a maximum on the axis of the pore and decreases to zero at the pore wall. Therefore, the particles in the flowing water will seldom if ever touch the surrounding grains that make up the pore walls. As the velocity of the water increases then the nature of the flow becomes much more complicated. Random irregular, local circular currents develop throughout the fluid, with a large increase in the resistance to flow. Flow of this sort is called turbulent.

The determination of whether flow is laminar or turbulent is aided with the use of the Reynold's number. The Reynold's number represents the dimensionless ratio of the inertia forces to the viscous forces of the moving fluid. For long, smooth pipes if the Reynold's number, R_e, is below 2,000 then flow is considered to be in the laminar regime. R_e can be calculated from Reynold's equation below:

$$R_e = (V) (D)/ (\nu)$$

where V = Mean velocity, (cm/sec)

D = Diameter, (cm)

ν = Kinematic viscosity, (cm^2/sec)

The kinematic velocity of water is approximately 1.13×10^{-2} cm^2/sec for the temperature range expected. This equation will now be used to determine at what critical velocity (and flow rate) at which the flow in the 30 cm diameter tube becomes turbulent.

To find the critical velocity in the 30 cm diameter tube at which the flow becomes turbulent first let R_e = 2,000. Using the previous equation with R_e equal to 2,000 and the known quantities of diameter equal to 30 cm and kinematic viscosity equal to 1.13×10^{-2} cm^2/sec the critical velocity is found to be 0.73 cm/sec. This velocity corresponds to a volumetric flow rate of 546 cm^3/sec (8.6 gpm). Thus, flow rates less than 8 gpm should be laminar while those flow rates above may be turbulent.

In soil, the use of the Reynold's equation to determine whether flow is laminar or turbulent requires making two assumptions. The first assumption is that the velocity of the water through the soil is related to the velocity in the tube by the equation below:

$$V_s = \frac{V}{n} = \frac{(Q/A)}{n}$$

Where: V_s = Velocity of water through soil (cm/sec).

Q = Volumetric flow rate, (cm^3/sec).

A = Area of the soil/tube, (cm^2).

n = Porosity of soil, (0.3 - 0.4 for sand).

The second assumption is that the effective diameter (pore space) in the soil is approximately equal to the median grain size, D_{50}. The D_{50} of the sand is equal to 0.07 cm and a porosity of 0.35 for medium dense sand; for a volumetric flow rate of 1 gpm the R_e is equal to 1.5. Reports in the literature indicate that an R_e in the range of 1 is the boundary between laminar and turbulent flow. Flows of 0.3 to 1 cm/sec (4 to 10 gpm) will have R_e of 6-15; and thus be turbulent. The existence of turbulent flow in soils is uncommon except in coarse sands and gravels. Lambe and Whitman [31] report of

evidence that Darcy's law (laminar flow) holds for silts to medium sands. From this we conclude that for coarse sands and gravels turbulent flow can exist provided the gradient is high enough. During our experiments the hydraulic gradient was between 10 and 20 and typically the hydraulic gradient in natural soil is less than one.

Flow rates of less than 1 gpm were necessary for laminar flow in the sand used in this experiment. It seems quite reasonable to expect that sounds from leaks will only be detected above the background noise levels in soils when the leak flow rates are significantly greater than the laminar or Dayceyian flow rates typically found in nature.

We shall present the results of experiments to detect sounds when water flows through rips in a liner material, and also the results of experiments to determine the amplitude of sounds reflected at the mesh and the water/soil interface and the attenuation of sounds in the laboratory and the field.

Acoustic Amplitude From Ripped Liner Material Versus Flow Rate--

A series of experiments were carried out to determine if water flowing through rips in liner materials might generate significant sounds that could be used to detect leaks from lined impoundment sites. PVC sheets, 30 mil thick, with a linear rip of 5 cm and 15 cm length respectively were placed under the mesh in the 4 meter column. The PVC was held by the same flange that held the mesh. The microphone was placed in the column 15 cm above the mesh. Water was allowed to flow down through the column. Figure 19 shows the noise amplitude observed as the water flow rate varied while passing through the 5 cm and 15 cm long rips. The background noise is also shown. We did not observe a significant increase in sound amplitude when the ripped liner material was present compared to when it was not present. Thus we do not expect the water flowing through the ripped liner to be a good source of sounds that will assist us to detect the source of a leak.

It must be noted here that though there was no significant increase in noise levels compared to the background noise of the system there was some sound produced. We carried out a series of tests to determine the approximate amplitude of these sounds by independently measuring the amplitude of the noise from the funnel and mesh reaching the microphone through the water/soil interface the mesh and the soil itself.

Quality Control Experiments

Acoustic Amplitude in a Screen Versus Flow Rate--

The first series of tests were to measure the amplitude of the sounds detected under various controlled conditions. First was the amplitude of sound detected at the microphone when water flows in the column. Next adding the screen keeping the microphone in the same location at 15 cm above the location of the screen. Figure 20 shows the amplitude versus water flow rate for these two conditions. Note that the noise level was greater at flow rates above 6 gpm when there was no screen present in the column than the noise level observed when the screen was present.

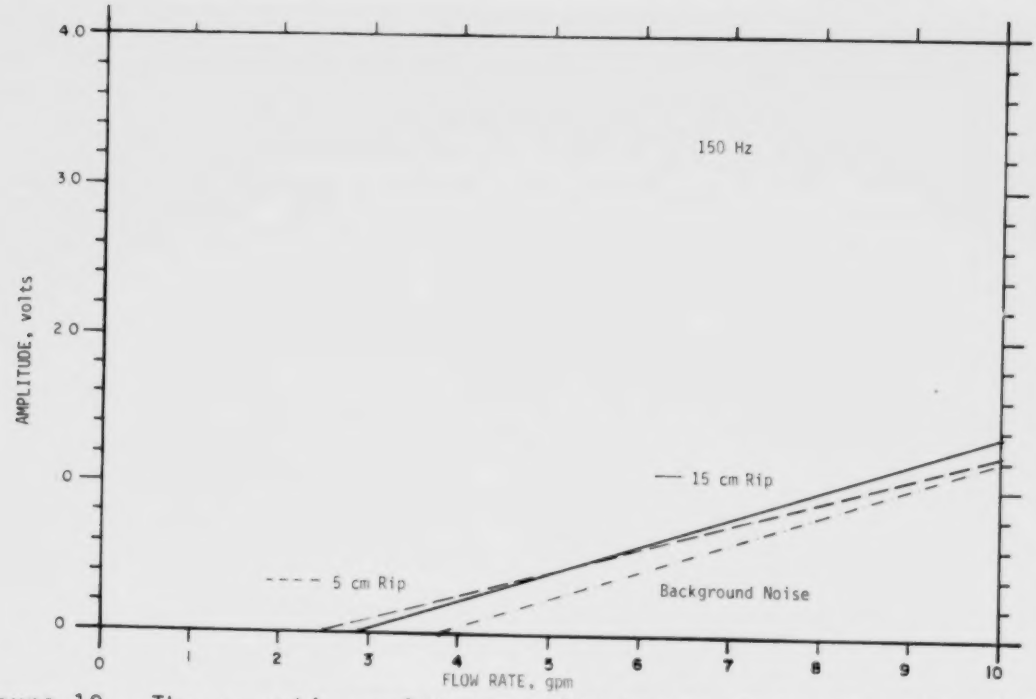


Figure 19. The acoustic amplitude at 150 Hz when water flows through the 30-cm-diameter tube at different rates through a linear rip of 5 cm and of 15 cm in a 30-mil-thick PVC liner material.

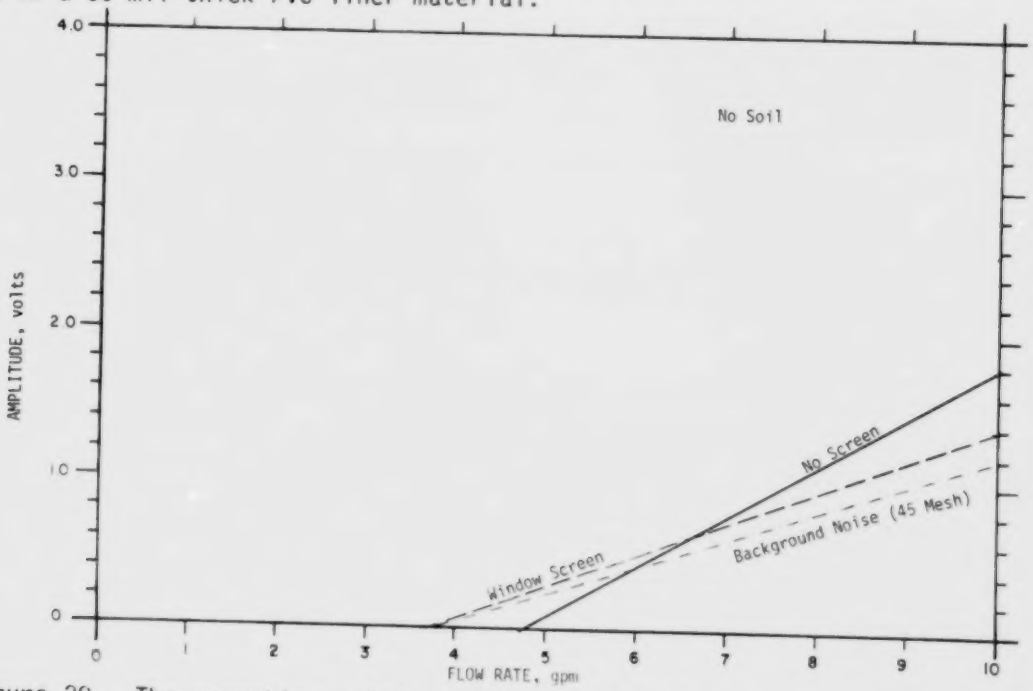


Figure 20. The acoustic amplitude of sounds detected when water flows through the system with no soil when the 45-mesh screen is present and when it is removed, and when a window screen is present.

An experiment using a screen with larger spacings than the 45-mesh screen was carried out. Figure 20 shows the amplitude of sounds detected using the two different screens. The response when no screen was present is also shown. The amplitude response from the screen with the larger spacings was slightly greater than the signal response from the 45 mesh screen. This indicates that the 45 mesh screen does attenuate or reflect some of the sounds from the funnel. At flow rates below 6 gpm the noise amplitude with the screen inserted in the column was greater than the noise level observed when there was no screen in the column. This indicates that the 45 mesh screen did produce some sounds when water flowed through it. These experiments indicate that the amplitude of sounds produced when water flows through the screens is small compared to the amplitude of sounds produced when water flows through the funnel.

A further test was carried out to determine the loss of sounds at the 45 mesh screen. We filled the column with water, left the microphone at a position 15 cm above the screen and inserted a loud speaker in the narrow part of the funnel. The loud speaker emitted sounds over the same frequency range, 20 to 450 Hz, similar to those detected when water flows through soils. Figure 21 shows the spectral data from 0 to 500 Hz, with and without the 45 mesh screen. The low frequency roll off is due to the speaker characteristics which will be discussed later. The sound amplitude was slightly less with the 45 mesh screen in place then when the mesh was removed. The difference is about the same as our measurement precision. This test procedure was not sensitive enough to indicate the absolute magnitude of the sounds reflected or attenuated by the 45 mesh screen.

Sound Amplitude Lost at a Water/Sand Interface--

The same procedure was used as described above except that compacted sand was added. Figure 22 shows the spectral data observed when the sand was added compared with the spectral data when only the 45 mesh screen was present. The sound amplitude was reduced by a factor of three when the compacted sand was put on the 45 mesh screen. Figure 23 shows the relative amplitude difference from the loud speaker to the microphone when the sand is compacted and when it is not compacted. The signal level was lower when the sand was compacted compared to the level observed when the sand was not compacted. We expect a larger reflection, or lower detected signal at the microphone of the audio signal at the water/compacted sand interface than at the water/noncompacted sand interface since the reflection coefficient increases as the density difference between the water/sand interface increases.

Sound Amplitude Lost in Sand--

One further test was carried out using the same equipment discussed earlier. The microphone was moved from a position of 15 cm above the 45 mesh screen to 45 cm above the mesh in 60 cm of compacted sand. Figure 24 shows the spectral data from this test. The differences are within the measurement precision of the equipment. Quantitative indications suggest the sounds were not strongly attenuated in the (water) saturated compacted sand.

This series of experiments indicates that about one third of the sounds produced in the funnel were reflected at the water/sand interface. Thus the background level shown as a reference on the figures was greater by a factor of

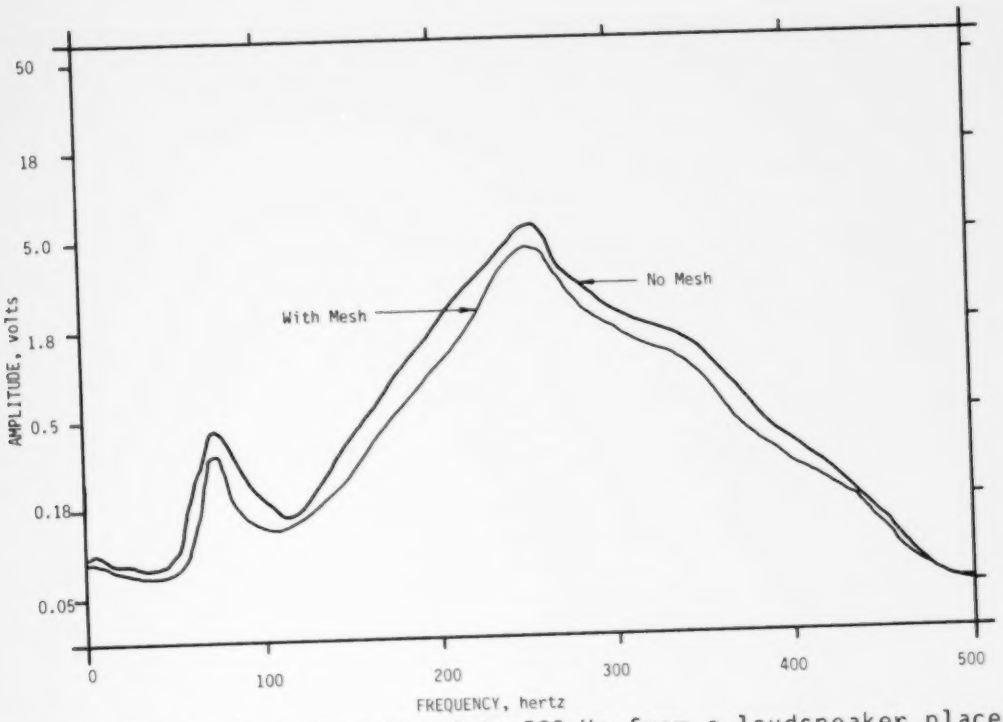


Figure 21. The spectral data from 0 to 500 Hz from a loudspeaker placed in the funnel and the 45-mesh screen is in place and when it is removed.

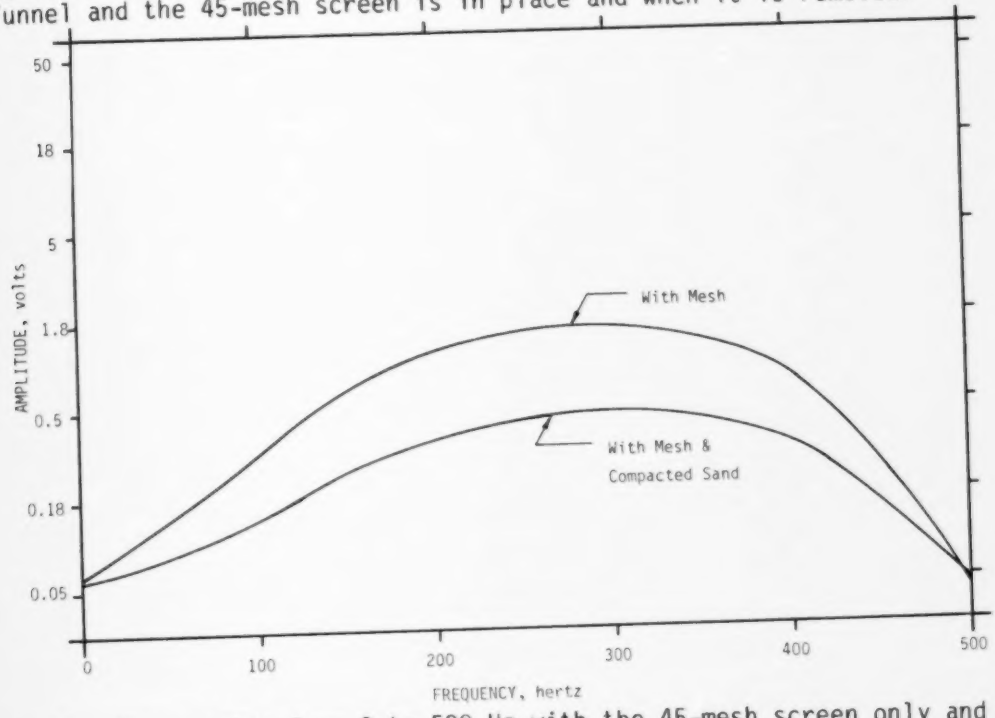


Figure 22. The spectra from 0 to 500 Hz with the 45-mesh screen only and with compacted sand placed on the screen.

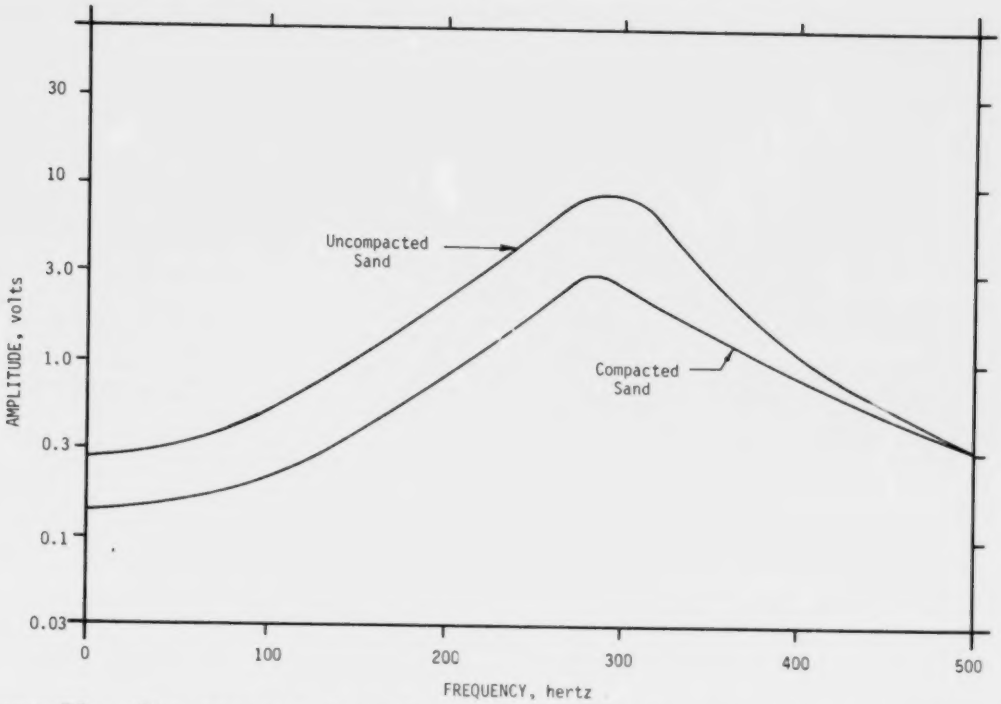


Figure 23. The spectra from 0 to 500 Hz with the microphone 15 cm from the 45-mesh screen with sand at two densities that differ by 8 percent.

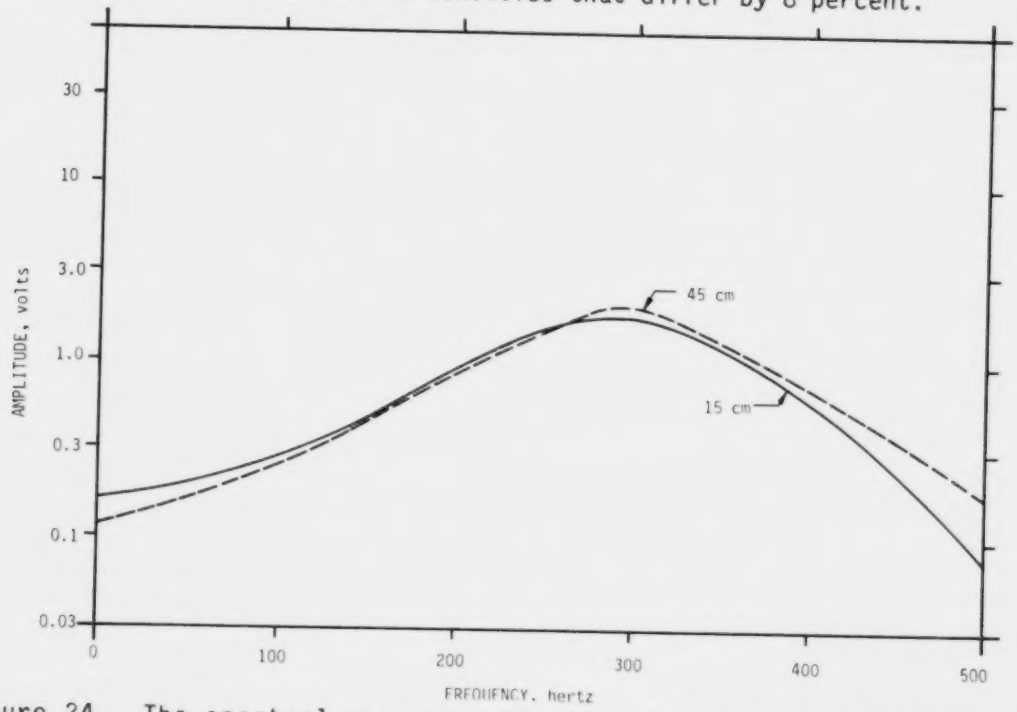


Figure 24. The spectral response when the microphone is moved 30 cm in a compacted sand.

three than the actual background level detected by the microphone in the soil. This accounts for the fact that many of the traces for sounds emitted when water flows through the soils apparently goes into the background noise at higher flow rates than does the response from the sounds emitted when water flows through the soil alone.

Error bars have not been put on the data but typically the noise on the amplitude of the spectral data is less than $\pm$0.1V throughout. The flow rates measured for each condition measured in the column were repeatable to $\pm$0.1 gpm.

Water Flow Rate Measurements--

Figure 25 shows the water flow rates versus head level when the 45 mesh screen alone was in the column, when 70 cm of pea gravel was added or when there is sand at 70, 100 and 150 cm length and when the PVC liner material with a 5 cm and 15 cm linear rip was in place. All the flow rates versus head level are essentially linear between 1 and 0.3 cm/sec (10 and 4 gpm). We note earlier that we have turbulent flow in the soils and thus we do not expect the

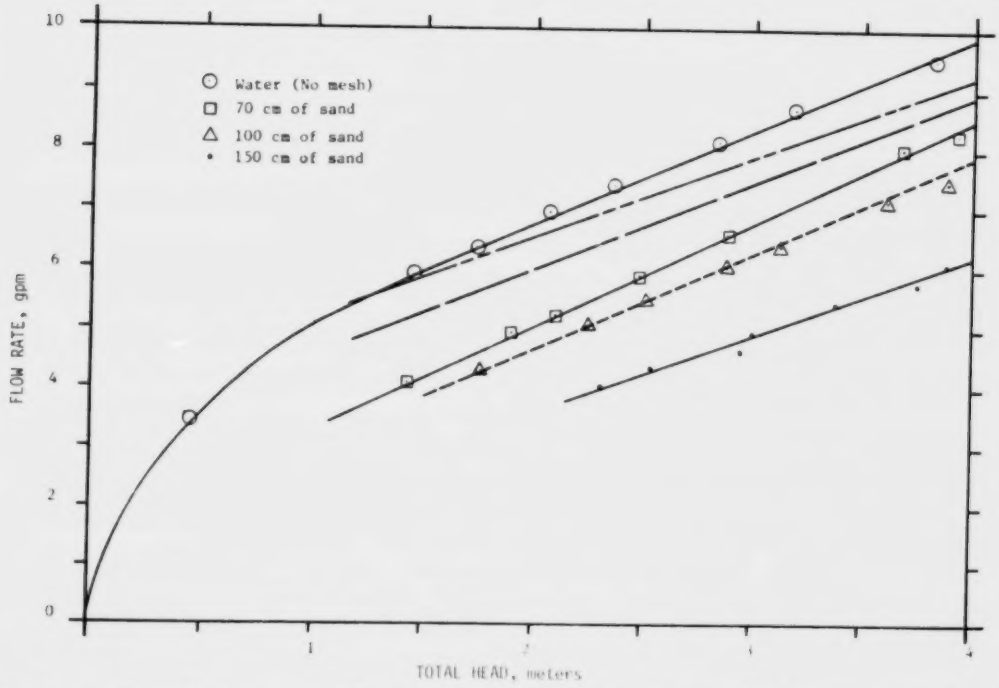


Figure 25. The water flow rate through the 30-cm-diameter tube at different water head levels when no soil is in the column, when different thicknesses of sand are in the column, when 70 cm of pea gravel is in the column, and when the PVC liner with 5-cm and 15-cm rips are in place.

linear response that we observe on the figure. The reason for this response observed is due to flow rates being primarily controlled by the plumbing of experimental arrangement and not by the materials in the column itself. The funnel is probably the major resistance element in the system and the Tygon™ tubing and the PVC valves are the next most significant impedances to the water flow in the system. We did not carry out a major analysis of the elements restricting the flow in the system. Using the response observed on Figure 25 we estimate that the permeability of the sand is 1×10^{-3} cm/sec.

Acoustic Response of the Electronic Equipment--

It is useful at this point in our discussion to show the response of the electronic equipment used. Figure 26 shows the amplitude versus frequency response of a) the sweep oscillator to the 466 Nicolet spectrum analyzer, b) the response when the Weston AEM was added and c) when the loudspeaker and microphone were added. The response in B shows the effect of the 80 Hz low frequency cut off of the filters in the Weston AEM. The microphone is simulated electrically by a 0.02μf capacitor in curve B. Curve C shows the effective frequency response of the loudspeaker used when it was under 20 cm of water. This response accounts for the low frequency roll off in Figures 21 through 24 and we shall see it again in the discussion about the field data. Keep

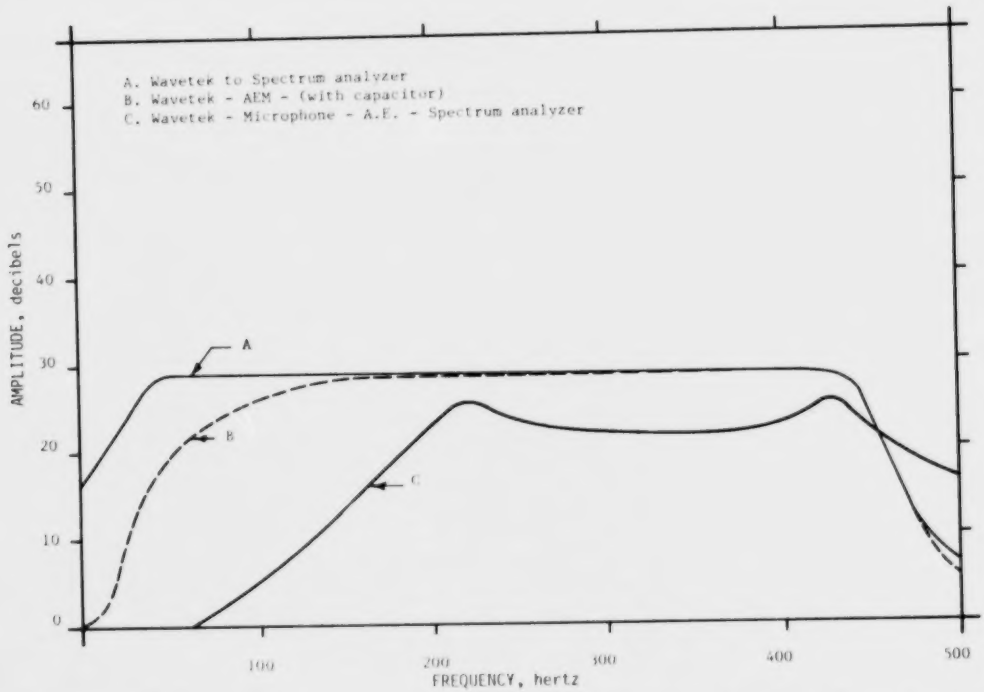


Figure 26. The spectral response from 0 to 500 Hz when a) the output of the sweep oscillator is fed directly to the spectrum analyzer, b) with the acoustic emission monitor amplifier and bandpass filter added, and c) also with a microphone and a loudspeaker both in water.

in mind that we are especially interested in relative changes rather than absolute measurements in these experiments.

We have now shown and discussed the most significant results obtained in the laboratory which were carried out to determine if sounds are produced when water flows through soils and the range of frequencies over which the majority of the energy of the sounds are emitted. We note that significant sound energy is produced at frequencies below 500 Hz when water flows through pea gravel and poorly compacted, well graded sand. Armed with this information we shall proceed to report the field results. The experiment carried out in the field was to determine the attenuation of sounds below 500 Hz in water.

Field Experiments

Sound Amplitude Lost in Water--

The method used was to move the loudspeaker that was emitting sounds from 20 to 450 Hz away from the microphone in water. The loudspeaker and the microphone were placed at a depth of about 20 cm below the surface of a lake. The water was about 2 meters deep. The loudspeaker would not work at a greater depth because the pressure on the diaphragm was not actualized. All the electronic equipment was placed in the back of a car and powered from an automobile lead acid battery.

Figure 27 shows the attenuation versus distance results at 400 Hz, 300 Hz and 200 Hz. The top solid line represents the theoretical case when there was no attenuation in the medium; the reduction of signal strength was due to the geometric spreading from a point source. The slope of the three lines at 400 Hz, 300 Hz and 200 Hz show that the attenuation in the water under the experimental conditions used was 10 dB/m. This attenuation value was about seven orders of magnitude higher than expected for sound waves at 100 Hz in water. The reason for the very high attenuation measured was not known for certain at this time but we strongly suspect that much of the sound energy at these frequencies was being lost to the production of waves at the water surface. We suspect that the loudspeaker was located too near the water surface and noticed that the attenuation decreased as the frequency increased which is not usually the case in water.

An expression for the attenuation coefficient of sea water from 100 Hz to 100 MHz is given by the following equation:

$$\alpha = \left[\frac{0.11 f^2}{1 + f^2} + \frac{0.70 f_t \, f^2 \, \frac{S}{35}}{f_t^{\,2} + f^2} + \frac{0.03 f^2}{f_t} \right]$$

$$(1 - 65 \times 10^{-6} d) \quad \text{dB/km}$$

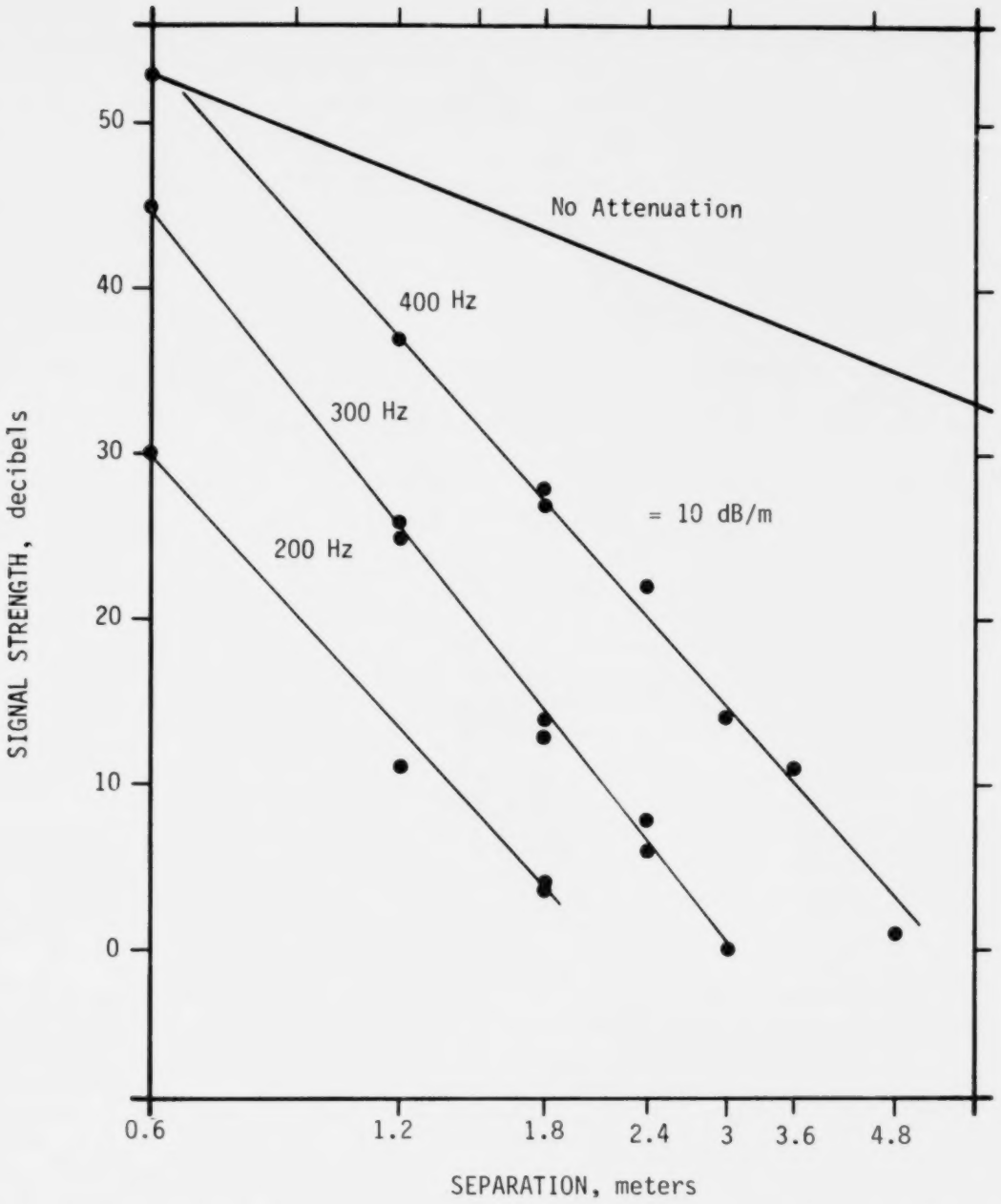


Figure 27. The attenuation of acoustic signals at 200, 300 and 400 Hz in water as the distance from the loudspeaker to the microphone is varied. The response when there is no attenuation and only geometric spreading losses are considered is also shown.

where f is the frequency in kilohertz

f_t is the relaxation frequency in kilohertz =

$$21.9 \times 10 [6 - 1.52/(t + 273)]$$

t is the temperature in degrees Celsius,

S is the salinity in parts per thousand

d is the depth below the air water boundary surface in meters (Fink & McKenzie, [19]).

Let $t = 20°C$

$f_t = 71$ KHz

$S = 0$

$d = 0.3$ m and

$f = 100$ Hz

then substituting these values in the above equation $\alpha = 1 \times 10^{-6}$ dB/m.

Note that the attenuation decreases as the depth increases. Fink and McKenzie also state that at frequencies between 100 and 1000 Hz, there exists a relaxation-type mechanism that is not well understood that dominates the attenuation. At frequencies below 50 Hz other attenuation mechanisms are of greater significance. The attenuation in fresh water may be somewhat different but clearly the attenuation of sound waves in water versus frequency is not likely to be a simple relationship.

Sound Velocity in Water--

We carried out an experiment to measure the velocity of sound waves in water. We used a 1 ms short burst pulse at 1.4 KHz and measured the propagation velocity of the sound waves to be 1,500 m/sec. The measured value is in good agreement with the textbook value at 20°C of 1,520 m/sec (Fink & McKenzie, [19]). The attenuation of the 1.4 KHz pulse was the same as that for the geometrical spreading losses and therefore very small. We also observed that harmonics from the sweep oscillator at frequencies between 450 Hz and 900 Hz which were down by 20 dB at the sweep oscillator output could be measured very well in the water and at a range much greater than the sound emitted at frequencies between 100 and 400 Hz which had a much greater source power. Further field experiments are necessary with the loudspeaker at a greater depth in the water.

Background Noise Level--

The background noise level observed in the lake of about 1 Km^2 located in Columbia, MD was 0.1V. This noise level increased to 0.5V from time to time depending on the cultural activity in the area and the waves on the lake

surface. This background noise level is about the same as that observed in the laboratory. These noise levels should be about equal to the noise typically found at a waste disposal pond site.

The typical threshold level setting recommended in the AEM manufacturer's manual for acoustic emission monitoring is 0.4V. The bandpass filters are usually set to cover 200 Hz or 50 KHz. Using the narrower bandwidth, below 500 Hz, suggested in this study permits us to be primarily sensitive to sounds emitted when water flows through soils. The unwanted noise produced at higher frequencies is eliminated and thus the background noise level in our measurements will be lower than the noise level used in acoustic emission monitoring; thus we will have greater sensitivity.

The results of the experiments and tests carried out in both the laboratory and the field show that acoustic sounds are produced at frequencies below 500 Hz when water flows at rates greater than 4 gpm through coarse grained soils. We also expect that the amplitude of the sounds emitted will be equal to or greater than the ambient background noise level in the field. The attenuation rate at frequencies below 500 Hz in water and soils was not determined explicitly in this study and further work is necessary. It is known in seismic soundings that generally the attenuation of sounds decreases as the frequency decreases and thus we expect the low frequency acoustic sounds emitted when water flows through soils to propagate well in a waste pond site.

SECTION 3

TIME-DOMAIN REFLECTOMETRY

INTRODUCTION

TDR is a high-frequency electromagnetic technique that can measure the electrical properties of materials in and around the conductors of a transmission line. The electrical properties of a leachate-saturated soil are usually different from those of the host soil material, and thus TDR can detect the leachate.

We envision that transmission lines placed under a liner material while the site is being constructed can be used for the TDR measurements. Commercial high-frequency transmission line conductors are usually about 1 cm apart, but our hope is to use transmission lines whose conductors are as far apart as possible--on the order of meters. Before a practical TDR system can be developed for detecting leaks under waste impoundment liners, tests will be needed to determine the practical problems with increasing the spacing between the conductors.

This section of the report begins with conclusions and recommendations for using the TDR technique in liner leak detection, followed by a review of TDR applications for electrical property measurements in geologic materials. The electrical properties of geologic materials are discussed, and then the principles of TDR are discussed, especially with respect to transmission lines and the TDR equipment. After the review, we discuss the TDR measurements carried out in the laboratory to determine the factors that affect the application of TDR for detecting and determining the extent of an electrical anomaly.

CONCLUSIONS

The TDR technique is a versatile method for obtaining electrical property measurements in soil. The electrical properties of a leachate in a soil can be assumed to be different from those of the soil host material under a waste impoundment liner. Many factors affect the electrical property measurements using the TDR technique. The purpose of this study was to determine the size of an anomaly (one that simulates a leak) that can be detected by the TDR technique as the spacing is increased between the conductors of a transmission line. The spacing between the conductors of an ideal transmission line should be small compared with the wavelength of the highest frequency of the TDR pulse. Transmission line conductors are typically about 1 cm apart. This requirement conflicts with that of having as few conductors as possible under a waste impoundment site. Thus, experiments were conducted to determine whether the

TDR technique could be used when the conductors were placed far apart (on the order of meters) as opposed to the small 1-cm conductor spacings in conventional transmission lines.

The experiments carried out in the laboratory were to determine (1) how the TDR signal response varies with the spacing between the conductors, (2) how the TDR signal response varies with the physical size of an anomaly, and (3) how the TDR signal response varies with the position and size of the anomaly relative to the transmission line conductors.

The laboratory experiment was designed to simulate an anomaly that could be detected by transmission lines. Boxes of sand, arranged in various configurations, were used to simulate the anomaly and the electronic equipment consisted of a TDR unit, an X-Y plotter, a parallel transmission line, and an electrical connector to connect the TDR unit to the transmission line.

Conclusions resulting from experiments carried out in this project are:

1) The TDR pulse signal rise time increases with the spacing between the conductors of a transmission line. The attenuation to the higher frequencies in the pulse increases with the frequency, and thus the TDR system resolution decreases as the spacing increases. In other words, the size of the anomaly in the transmission line must increase with the transmission line spacing to produce the same TDR reflected signal amplitude.

2) The TDR signal amplitude does not vary when the TDR signal travel time in the anomaly is less than or equal to the total travel time necessary for the signal to propagate through the anomaly. As the electrical length of the anomaly decreases below the pulse travel time in the anomaly, the signal amplitude decreases.

3) The TDR signal amplitude varies slightly with the height of the anomaly (i.e., the dimension whose axis is perpendicular to the plane of the conductors in the transmission line varies as long as the height of the anomaly is at least three times greater than the diameter of the conductors).

4) The amplitude of the TDR signal is greatest when the anomaly touches both conductors of the transmission line. The signal amplitude decreases significantly as the width of the anomaly decreases relative to the spacing if the anomaly is touching one of the conductors. (See Figure 28)

These conclusions led us to generalize that a cube-shaped anomaly whose sides are equal to at least half the spacing between the conductors will have a TDR signal amplitude of about one-fifth the maximum signal amplitude that would occur if the transmission line penetrated an anomaly that was very large relative to the spacing of the transmission line conductors. This generalization will be affected by a number of factors that we have not included in our studies. The electrical loss properties of the materials likely to be found in the field will reduce the TDR signal amplitude. Thus the size of the anomaly will have to be increased to increase the reflected TDR signal amplitude. The electrical property contrast of the leachate-saturated soil relative to that of the host soil under the waste impoundment may not be as great as the electrical

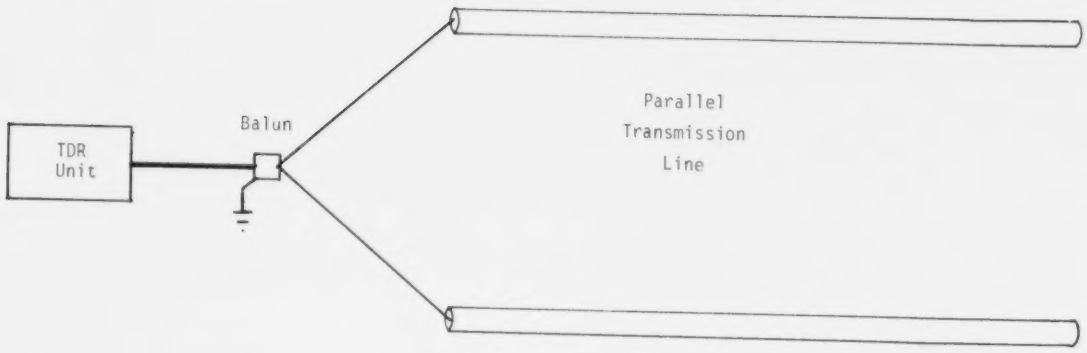


Figure 28. Schematic diagram of the TDR system.

property contrast we used in our model; thus the reflected signal amplitude may not be as large in the waste site environment.

The model used in these experiments only tested the TDR response in transmission lines whose maximum spacing between the conductors was 2 m. Larger spacings between the conductors are practical using the same TDR unit, but experiments to determine the maximum spacing of the conductors still need to be carried out.

The TDR technique appears to be a practical method for detecting and determining the position and extent of a leachate under a small waste impoundment liner. A cube-shaped leak with dimensions on the order of one-half of the spacing between the conductors of the transmission line is about the minimum practical size that can be detected using the TDR technique.

RECOMMENDATIONS

This project was a preliminary study to determine whether the TDR technique has practical potential for detecting a leak from a waste impoundment liner. A review of its application to measurements in the field showed that the technique is very versatile and that many factors affect the TDR measurement. The laboratory studies indicate that TDR could be used with transmission lines that are electrically very large relative to conventional high-frequency transmission lines.

These preliminary studies of the TDR technique permit us to recommend further tests that need to be carried out before a practical TDR system can be emplaced in the field under a waste impoundment liner. The recommendations based on this study are:

1) Experiments should be carried out using simulated leaks over transmission lines at different conductor spacings placed in a sandy soil about 1 m thick.

2) Based on the results of the above experiments, a series of transmission lines should be designed with different spacings between the conductors and placed in a sandy soil under a lined pond filled with water. The lengths of the transmission lines should be varied up to about 30 m. Controlled leaks in the liner should be used to test the ability of the TDR system to detect leaks of different sizes and positions around the transmission lines.

3) A TDR system field design configuration and cost analysis should be carried out after the above tests have been made.

4) TDR equipment should be designed specifically for detecting leaks at actual waste impoundment sites. Possibly a higher-power pulse of longer duration would make the TDR system more economical for detecting leaks at large waste impoundment sites.

5) The best materials for transmission line conductors should be determined to minimize corrosion in a waste impoundment environment.

6) The high-frequency (1 to 1,000 MHz) electrical properties of some leachate-saturated soils and of soils typically found under waste sites should be determined.

Results of the recommended research will help us define the usefulness of the TDR technique for detecting leaks and for determining the extent of leaks from a waste impoundment liner. Such studies would also help us to design a practical TDR system for monitoring leaks from waste sites.

METHODS

In this section, we describe the laboratory experiment to determine the size of anomalies that can be detected as the spacing of the transmission line conductors is increased. The equipment consisted of a TDR unit, an X-Y plotter, a parallel transmission line, an electrical connector to connect the TDR unit to the transmission line, and boxes filled with dry sand to simulate an anomaly. Each of these units will be discussed briefly. The method by which the experiments were carried out will also be discussed.

The TDR instrument used for these experiments was a Tektronics Model 1502 cable tester. This is a portable field unit that has the pulser, receiver, and display units in one package. The pulser produces a step pulse with a rise time of 1×10^{-10} seconds. The receiver uses a sampling technique to produce an audio frequency facsimile of the radio frequency signals. The receiver has a sensitivity of 2 mV. The unit displays an audio frequency

facsimile of the radio frequency pulse on an interval oscilloscope. This unit also comes with an X-Y output module which was used with an X-Y plotter to obtain a paper copy of the TDR traces.

The transmission line used was a parallel-wire transmission line. The two conductors of the line were made of 6-m-long aluminum tubes with a 5-cm-outside diameter. These tubes were supported on a wooden frame so that the spacing between the tubes could be varied. The spacings we used were 10, 20, 40, 60, 80, 100, 120, 150, and 200 cm, which allowed us a great deal of flexibility.

It is important to get as much of the signal from the TDR unit on and off the transmission line. A special electrical connector arrangement to connect the TDR unit to the conductors at the different spacings was designed and built at EarthTech. The connector consisted of a 50-to-200-ohm balun transformer and two sheets of metal to connect the transformer to the aluminum tubes. The metal sheets were designed to provide a gradual impedance transition from the transformer output impedance of 200 ohms to the conductors of the transmission line which had impedances varying from 200 to 600 ohms. The 50-ohm input impedance was matched to the output impedance of the TDR instrument. Figure 28 is a schematic diagram of the TDR unit, the connector, and the parallel transmission line. Figure 29 is a photograph showing the actual connector arrangement (the triangular-shaped device connected to the aluminum pipes). The TDR instrument is on the floor in this photograph.

The anomalies that might be found in the field were simulated in the laboratory by boxes filled with dry sand. Each box was a 15 cm cube. The boxes were placed side by side and on top of each other in order to increase the size of the overall anomaly. This arrangement worked very well (Figure 30). The sand had a dielectric constant of 3.5. The TDR signals in the sand had a propagation velocity of 1.6×10^8 m/s, which was nearly half of the propagation velocity in free space. The boxes of sand were equivalent to a leachate-saturated soil in a soil host material with a volumetric water content of about 20 percent. The electrical losses in the air and the sand were negligible to the TDR pulse used. This arrangement provided a satisfactory initial model of an actual field setup under a waste impoundment liner.

REVIEW OF TDR APPLICATIONS IN GEOLOGIC MATERIALS

Overview - TDR Measurements

Time-domain reflectometry is a wide-frequency-bandwidth, short-pulse-length measurement technique that is sensitive to the high-frequency electrical properties of the material in and around the conductors of a transmission line. The high-frequency (10^6 to 10^9 Hz) dielectric properties of water in its liquid state are about 20 times greater than the high-frequency dielectric properties of dry geologic materials. Thus TDR is primarily sensitive to changes of water content in geologic materials and relatively insensitive to changes in soil type, density, and temperature, and in pore liquid salt content. In materials with a relatively uniform water content, TDR is sensitive to changes of soil and rock

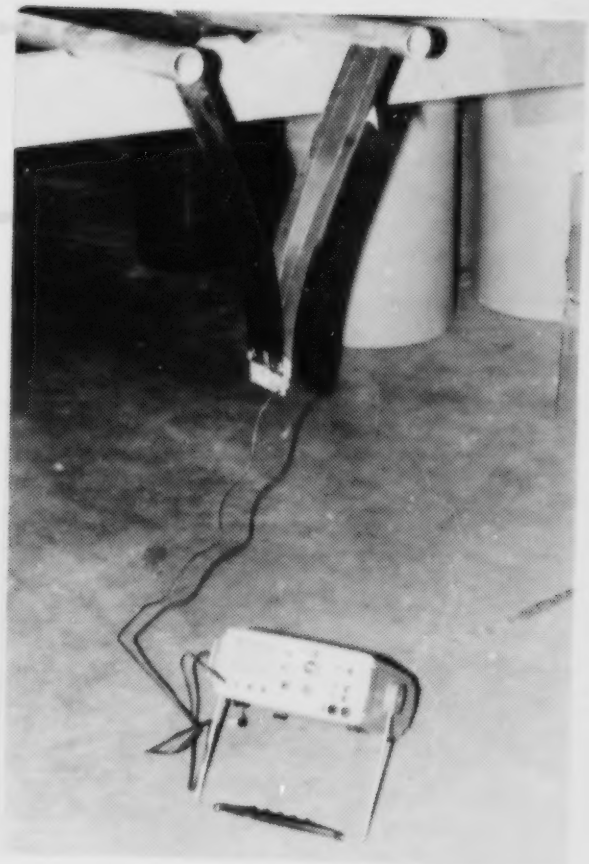


Figure 29. Photograph of the TDR system.

Figure 30. Anomaly placed between the transmission line conductors.

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type. This method is also sensitive to changes in the phase of the water molecule, and thus frozen or unfrozen wet soils. In addition, TDR can detect either water- or air-filled fractures in the materials along the transmission line.

Leaks from liners of waste impoundments into the soil below are likely to have different electrical properties from those of the host material. Thus TDR can measure electrical property variations in the material along a transmission line. The TDR technique, using transmission lines placed under a liner, offers the significant potential of being a practical method for detecting small leaks from waste dump sites.

TDR has been applied to measurements of geologic materials for fewer than 10 years, and therefore much of the work to date has been carried out to determine the practical applications and limitations of the technique. The main use of TDR has been for testing transmission line cables such as those used in radio and telephone communications and in high-voltage transmission lines.

The electrical properties of geologic materials, especially soils, are very complicated at first glance. But over the frequency range we are interested in (10^6 to 10^9 Hz), the dielectric constant is primarily sensitive to changes in water content and has a relatively weak sensitivity to changes in soil type, density, and temperature, and in soluble salt content. TDR has shown excellent potential for carrying out useful electrical measurements of geologic materials.

The TDR equipment is coupled to the geologic medium by a transmission line. The latter can be used to measure the electrical properties of materials in the lines. A transverse electromagnetic (TEM) wave, having the same properties as a TEM wave in free space, propagates along the transmission line in the dielectric material between and around the conductors, which act as guides for the waves.

This review of TDR application in geologic materials begins by showing examples of where TDR has been used to carry out electrical measurements along transmission lines, primarily in geological materials. The normal uses for TDR are described, and examples are given of work carried out to determine the potential usefulness of TDR measurements of the high-frequency electrical properties of geologic materials. Most of the examples described here deal with using TDR to carry out soil water content measurements. This is an application where TDR appears to offer the greatest practical measurement potential at present.

Classic Uses of TDR--

TDR, using fast rise time pulses of short duration to evaluate transmission lines was developed in the early 1960's. The main use of TDR was for testing transmission line cables such as those used in radio and telephone communications and in high-voltage transmission lines. Faults in any of these transmission lines cause severe signal distortion and substantial power loss.

Transmission line cables may deteriorate and change with time, water may leak into the cables or connectors, conductors may open or short circuit, contacts may corrode, a clamp may be fastened too tightly, or an insulator may break. These faults will cause signal reflections in the transmission line, which

otherwise has uniform electrical properties. If the signal propagation velocity in the cable is known then the TDR, which measures time precisely, is used to determine the location of the fault in the line.

In the field the TDR instrument is connected to the transmission line under test. Pulses are sent along the line; if there are any faults in the line, then part of the pulse signal is reflected and part of the signal continues on. The reflected signal is detected by the TDR receiver, processed and displayed. The signal travel time and signal amplitude permit the engineer to determine the location and nature of the fault along the transmission line.

Physical chemists use TDR to measure the electrical properties of different chemical solutions. Time-domain reflectometry is also used to identify various chemicals and their composition. TDR can also measure the thickness of one chemical on another.

TDR Measurements in Geologic Materials--

Experiments to determine the usefulness of TDR for soil water content measurements have been carried out in Canada, at the Geological Survey of Canada and the Department of Agriculture, since the mid-seventies [9, 11, 13, 14, 45, 46, 48, 49]. A brief summary of their work shows that the dielectric constant, measured by TDR is strongly dependent on the volumetric water content and only weakly dependent on the soil type, temperature density and solution salt content (Topp, et al., [45]). They have shown that parallel transmission lines placed in soil is a practical method for measuring soil water content in the field (Topp and Davis [47]). A few results of the work carried out to determine the potential of TDR to carry out electrical measurements of geologic materials both in the field and the laboratory follows.

Topp, Davis and Annan [45] report on extensive laboratory measurements to determine empirically the relationship between the volumetric water content and the apparent dielectric constant, by measuring the propagation velocity of a TDR signal in a coaxial transmission line filled with soils at different water contents. The soils they tested varied in texture from sandy loam to a clay loam and finally a heavy clay. Figure 31 shows the results of their experiments. The solid line is the empirical best-fit. The dashed lines are shifted ± 0.025 in water content and they encompass 93 percent of the data points.

Topp, et al., note that the clay soil showed a lower apparent dielectric constant at water contents around 0.1 $cm^3\ cm^{-3}$ but a higher apparent dielectric constant when the water content was increased to 0.40 $cm^3\ cm^{-3}$ than was observed for the sandy loam soil. This effect was also observed for vermiculite and an organic soil. They also carried out experiments using 30 m and 450 m glass beads. The results of these experiments are shown in Figure 32. The trend of water content versus apparent dielectric constant for these materials is similar to that of the soils. The offset of the curve for glass beads at very low water contents is due to the higher dry dielectric constant, $K_a \approx 3.5$ of dry glass beads as opposed to $K_a \approx 3$, for dry soil.

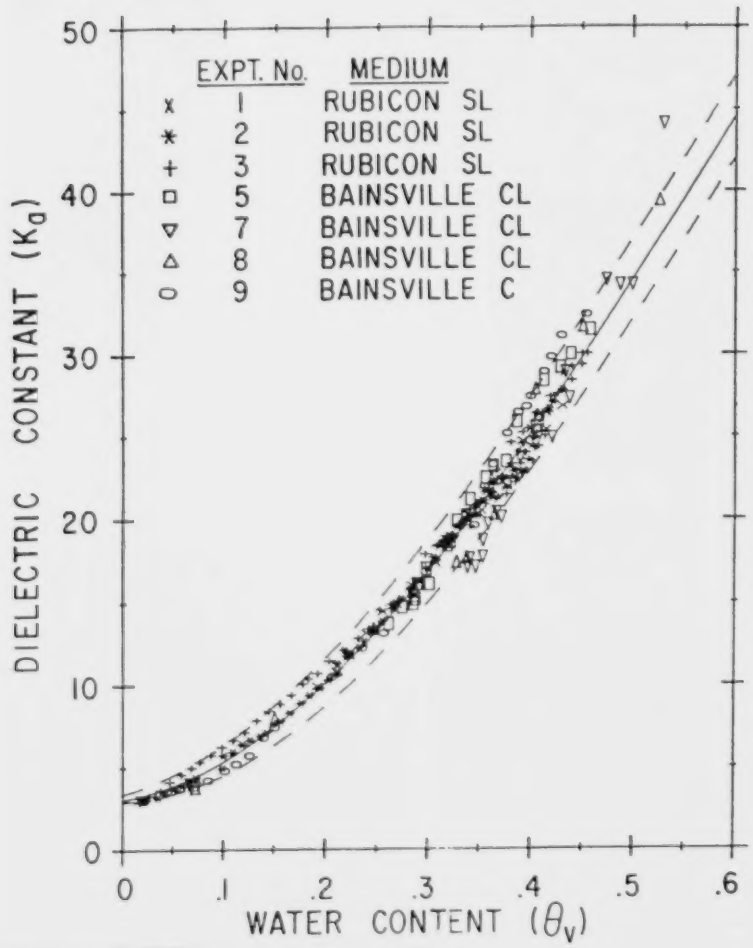


Figure 31. The measured relationship between the dielectric constant and the volumetric water content for four mineral soils. The solid line is the empirical best-fit equation and the dashed lines are shifted +0.025 to include 93 percent of the data points. (From Topp, et al. [45])

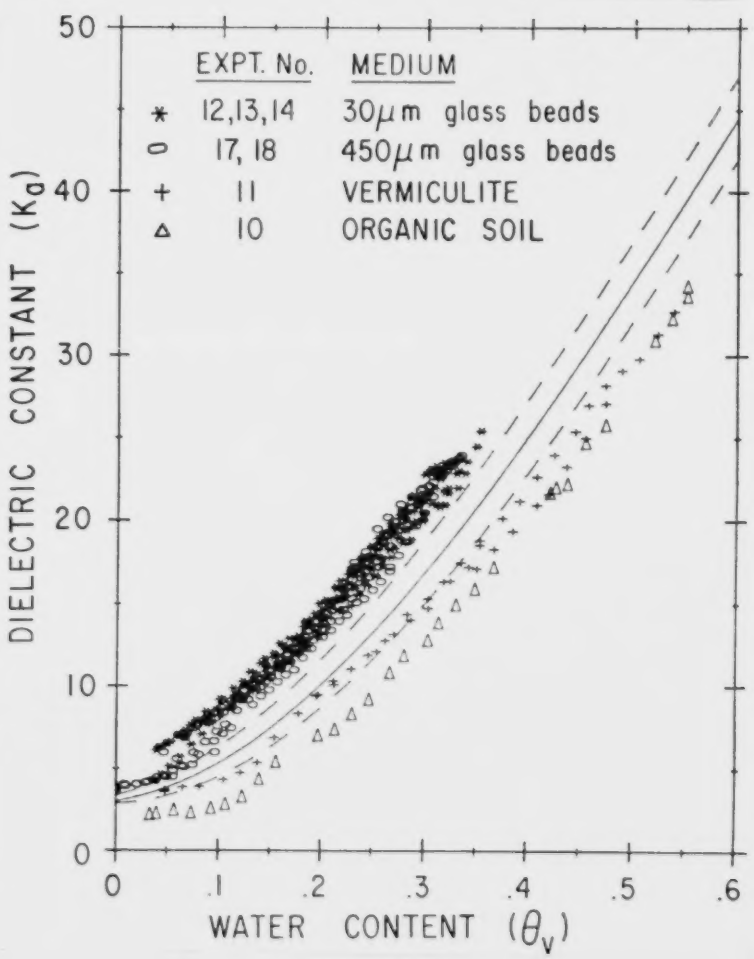


Figure 32. The measured relationship between K_a and θ_v for 30 and 450 μm glass beads, vermiculite, and an organic soil. The area between the dashed lines represents the same area as in Figure 32 for the mineral soils. (From Topp, et al. [45])

They offer an explanation for the greater curvature in the water content versus dielectric constant for the fine grained soils, such as clay, and the vermiculite and organic soil, based on the possibility that the active surface area of the soil controls the dielectric properties of the first few molecular layers of water added to the soil. The first molecular layers of water, being tightly bound to the soil particles, have a dielectric constant approaching that of ice.

It is interesting to note that the Topp, et al., curve agrees well with the curve reported by Patterson and Smith [38] using TDR and relating the unfrozen water content in frozen soils. The curve also agrees well with that given by Sweeny and Colbeck [43] on wet snow samples at water contents up to 0.2 obtained at a measurement frequency of 6 GHz. This is not too surprising since the dielectric constant of frozen soils is about 3 and that of snow is about 2.

Topp, et al., note that a series of calibration TDR measurements on the particular soil under study can give greater precision to ± 1 percent of water content from the measured dielectric constant that is shown in Figure 31.

They present a graph (Figure 35), showing the relationship between the dielectric constant and water content for a sandy loam soil having in one case a water solution of 0.01 normal calcium sulfate, and in the other case the water solution with 2,000 parts per million sodium chloride. The resultant curves showed no measurable difference. They carried out a similar experiment using glass beads and the results were the same. The dissolved salt did not alter the propagation velocity of the TDR pulse in the medium, but the attenuation to the pulse increased significantly.

Increasing the dissolved salt content in the pore water increases the signal attenuation. Similarly, when the soil grain size decreases or the soil temperature increases, the attenuation to the TDR signal increases. This increase in attenuation does not measurably alter the propagation velocity but it does lengthen the pulse rise time significantly and thus decreases the system's resolution. As the attenuation increased due to the increase in salt content, temperature, or decrease in soil grain size, the scatter in the data increased although the basic trend remained the same.

Topp, Davis and Annan [48, 49] report on extensive work in the laboratory to simulate actual field conditions, using parallel-balanced transmission lines, that were about 1 m long, placed in a tank filled with a silt loam soil. They evaluated different types of transmission line designs and installation techniques, comparing the volumetric water content obtained from gravimetric samples and TDR measurements. Results of the TDR response in nonuniformly wet soils was shown, and examples of using the TDR to detect and monitor the progression of a wetting front through a soil was also given.

Briefly, they conclude that TDR applied to parallel transmission lines is an effective method of measuring soil water content. An average discrepancy of ± 0.03 gm^3 gm^{-3} between water contents measured gravimetrically and those measured by TDR was observed. They believe a significant proportion of the difference is related to real variations in the soil such as density, and wetting and drying patterns affecting the water content in the different measurement

locations. Figure 33 shows Topp et al.'s [49] results comparing the TDR soil water content measurements with the water content added for two different transmission line types; one type having no discontinuities and the other having discontinuities filled with a high dielectric constant material. They discuss in detail the effect of having air in the discontinuity and they do not recommend this type of line.

They note that the transmission line installation technique is not critical providing that the soil is tightly contacting the conductors and no cracks are produced in the soil between the conductors. They recommend that slightly undersized pilot holes be drilled before the conductors are inserted so that soil density variations around the conductors are reduced.

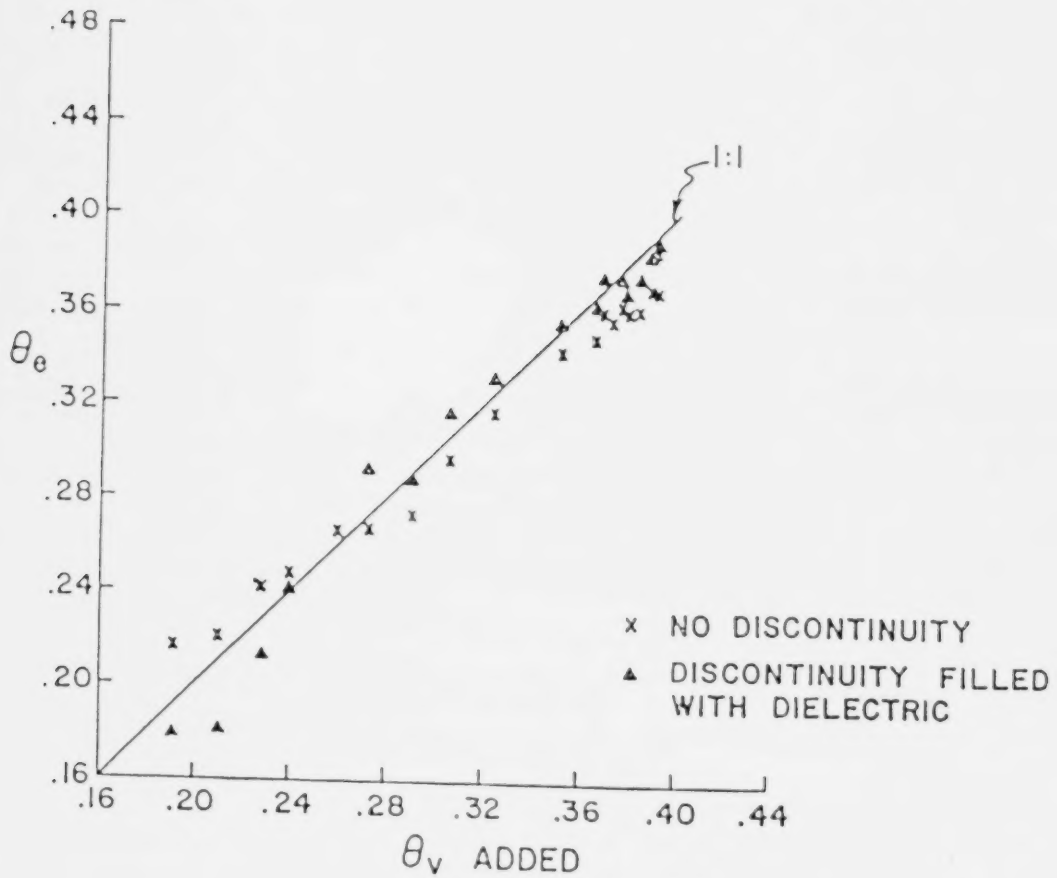


Figure 33. TDR measured water contents, θ_e, from two different types of transmission lines, compared with known water content from additions and removal of water from the soil. (From Topp, et al. [49])

They also show a comparison of water content profiles to 1-m depth as measured by TDR lines and by gravimetric sampling which is shown in Figure 34 here.

Their Part I paper shows that TDR is a practical technique to measure the soil water content averaged over the measurement length even when steep gradients or wetting fronts are present. They also show that TDR can measure the distance to wetting front and the water content ahead of and behind the wetting front. Figure 35 is from Topp, et al.'s [48] Figure 8 and shows distance to the wetting front versus time as measured by TDR and the distance to the wetting front when the amount of water added and the soil porosity are known. The measurement trends of the two methods agree extremely well. The slight differences, about 5 cm, in actual distances is likely due to a decrease in soil density between the transmission line conductors. The soil was packed around these lines before water was added. A decrease in soil density between the conductors in the line will cause an initially rapid infiltration into such soil while being wetted, followed by a decreased rate after wetting has ceased. Figure 36 shows a comparison of the depth of water added as measured by TDR with that added from the rising water table experiment for transmission lines packed with dry soil and dielectric filled lines. The agreement between the two techniques for both line types is very satisfactory.

Topp and Davis [47] have carried out TDR measurements in the field to evaluate its practical measurement capability. They conclude that the accuracy of the soil water content as measured by TDR compared very well to that of gravimetric measurements. The limit of accuracy appears to be dependent upon soil variability. When both methods sampled the same soil the standard deviation of the differences was 0.02 cm^3 cm^{-3}. When the measurements were not of exactly the same soil the deviation of the differences was 0.06 cm^3 cm^{-3}.

This result is very exciting indeed. The TDR method appears to have similar accuracy to the generally recognized field water content measuring method. What is even more encouraging is that the TDR technique is not destructive to the soil itself as is the gravimetric method. Repeated TDR measurements can be made on the same soil, thus reducing the effect of soil variability on the measurements.

There are many examples in the literature discussing applications where TDR has been used to make measurements in geologic materials. We shall describe briefly some of the work here for the reader to see the versatility of the technique.

Baker and Davis [3] show results of laboratory studies to determine the TDR accuracy compared to temperature for measuring the location of the freezing point in water, a sand soil and a clay soil. The dielectric constant of ice and frozen soils is about 3 compared to 81 for water. They note that the TDR measurements agree with the other measurements to within 1.0 cm. Once again each technique has errors and the measurements are sensitive to slightly different properties. Annan and Davis [2] and Baker et al. [4] show field measurements where the TDR was used to measure the depth of frozen ground versus time over the winter months.

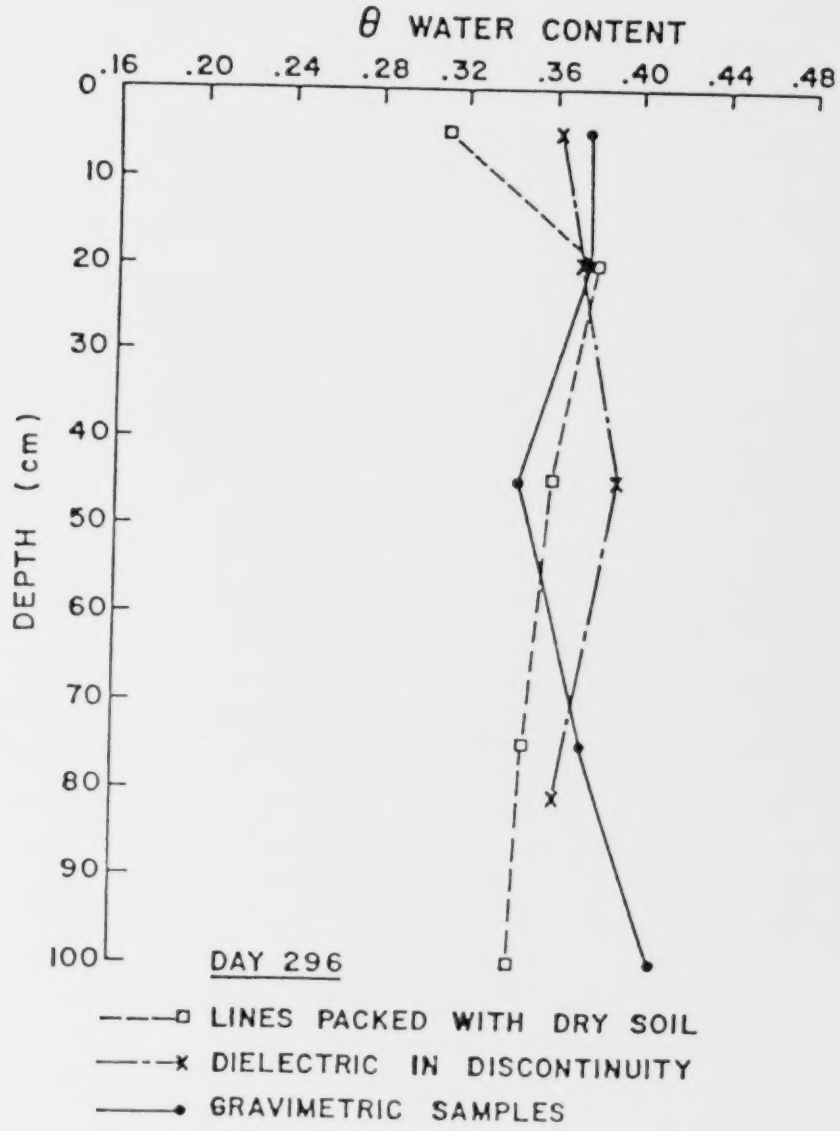


Figure 34. Water content profiles as measured by two types of TDR lines and by gravimetric samplings. (From Topp, et al. [49])

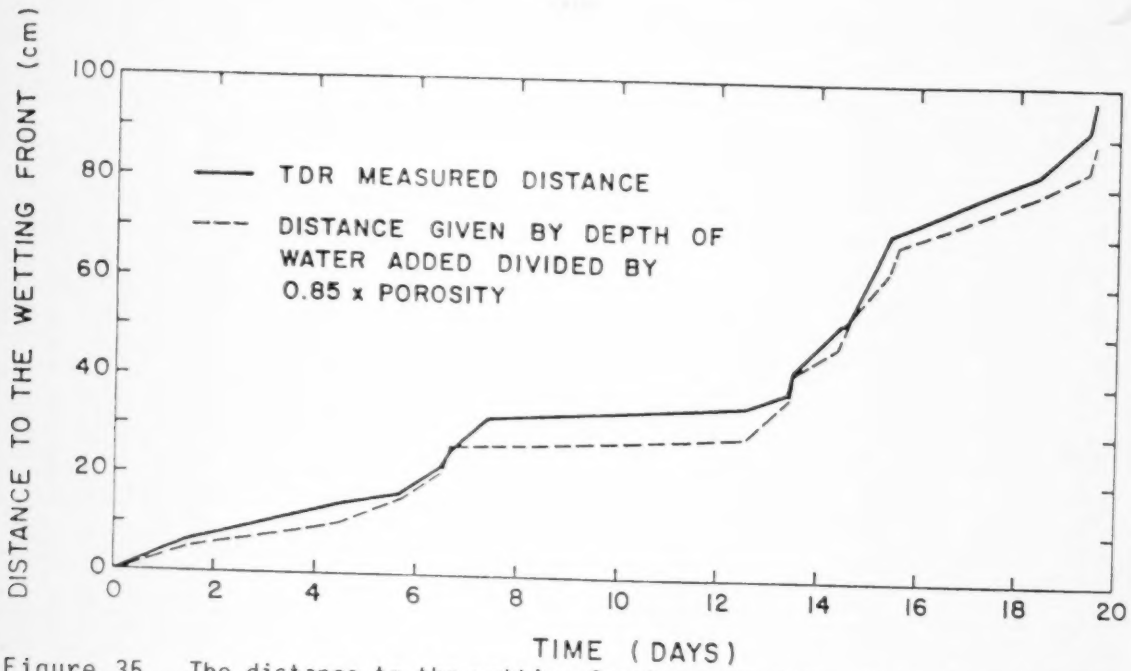


Figure 35. The distance to the wetting front versus time, as measured by TDR is compared to the distance obtained by knowing the volume of water infiltrating the soil and assuming the pore space is 85 percent water saturated. (From Topp, et al. [48])

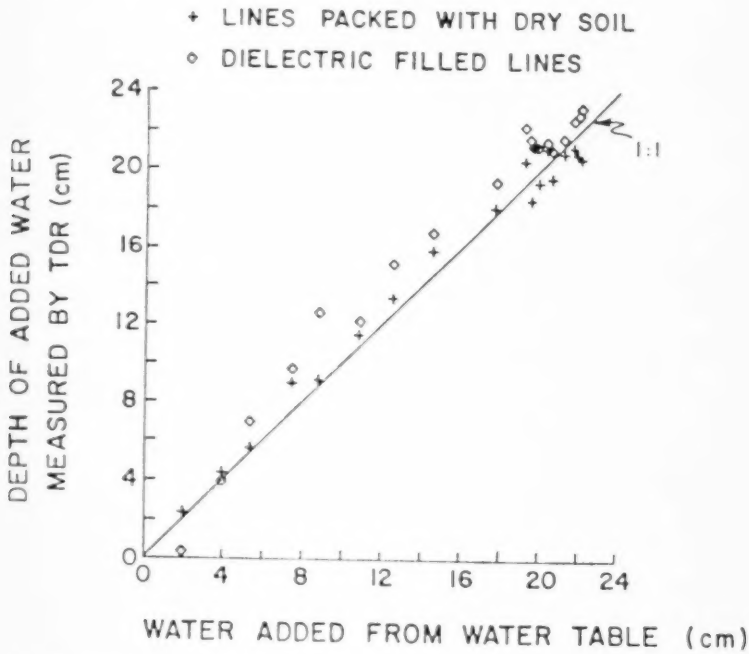


Figure 36. Comparison of depth of water added as measured by TDR with that added from the rising water table.

Keng and Topp [28] compare the water content measurements made by the TDR and a single beam gamma ray attenuation technique. Their error analysis showed that the gamma ray measurements of water content had an uncertainty of ± 0.05 cm^3 cm^{-3} for three soils. The variability of soil bulk density was probably the main source of the error. The TDR technique had a total uncertainty of ± 0.02 cm^3 cm^{-3}. The greater sampling volume of the TDR is advantageous when measurements of naturally structured heterogeneous soils are made.

Topp and Davis [46] discuss using TDR in the field to measure the infiltration of water through soil cracks. Davis and Annan [12] report on using TDR to measure the electrical properties of potash (KCl), salt (NaCl), and clay in a potash mine to determine the potential of carrying out short-pulse radar surveys in the mine. The TDR and radar data agreed very well. Davis [10] carried out TDR measurements in first year sea ice to determine if there is any variation in the electrical properties of the sea ice with orientation of the electric field in the horizontal plane. He did not observe any significant variations, although radar signals reflected from ice/water interface vary depending upon the orientation of the electric field of the antennas at the ice surface.

TDR experiments have been carried out to measure the curing rate of concrete. Studies are presently underway in this project to determine the potential of using TDR lines placed under hazardous waste impoundment liners to detect leaks. These experiments show that dielectric contrasts of 2:1 with the host material and that have a physical dimension of half the conductor spacing in all planes can be detected.

It is clear that TDR offers great potential for monitoring the high-frequency electrical properties of geologic materials. These properties can then be related to practical measurement needs like soil water content or depth of frozen ground. The TDR equipment can be easily adapted for control by a microprocessor even in remote areas. The data can be processed and interpreted by a small computer and the results can be stored either in a digital or an analog format.

Summary--

This section presented examples of work carried out both in the laboratory and in the field showing the usefulness and accuracy of TDR techniques when applied to geologic materials. We note that the high frequency, 10^6 to 10^9 Hz, dielectric constant is primarily sensitive to the volumetric water content in soils and is only slightly sensitive to the soil type, temperature, density, and soluble salt content.

Many of the examples discussed here give evidence of the above statement. The examples showed that the TDR technique can be applied practically to carry out soil water content measurements in the field. The initial TDR measurement results compare very favorably with gravimetric measurements of soil water content in the field.

Examples are then offered showing that the wetting front and the freezing front in soils can be measured. Mention is made of TDR measurements in a potash mine, and in sea ice to determine their electrical properties. The electrical property measurements were then used to help interpret short puise radar soundings. It is clear that the TDR technique can be used to obtain practical information about geologic materials. The TDR technique has high resolution and is sensitive to small changes of electrical properties in complex geologic materials. However, many factors can and will affect TDR data, thus making very careful equipment set up critical and data interpretation difficult.

Overview - Electrical Properties

Introduction--

Time-domain reflectometry has shown excellent practical potential for carrying out useful electrical measurements of geologic materials. In this section we shall discuss in very general terms, and only briefly, the electrical properties of materials and, more specifically of geologic materials, especially heterogeneous materials such as soils.

References on the fundamental principles are listed in the bibliography since a discussion is beyond the scope of this review.

The general overview of the high-frequency electrical properties given here shows the complexity of geologic materials and, at the same time, indicates some of the major and minor variables so that meaningful measurements can be carried out within certain finite limitations. The advantages of the frequency range of the time-domain reflectometer for measurements of geologic materials is also shown.

Dielectric Materials--

In very simple terms a dielectric material is an insulating material and, thus, does not contain free electrons. Each electron is bound to the ionic lattice by the electrostatic attraction between the negative electronic charge and the positive charges on the nuclei. In the absence of any external field, the electrons are distributed symmetrically with respect to the nuclei. When an external electric field is applied, the electron clouds are displaced in the direction opposite to that of the field, while the more massive nuclei are only slightly displaced in the direction of the field. (The center of gravity remains fixed). The atoms, thus, are distorted or polarized as shown diagramatically in Figure 37. There is no resultant charge density within a simple uniform dielectric, as all the individual dipoles are aligned parallel to the field; thus each negative charge of one dipole is next to the positive charge of the next dipole.

The electric polarizability is a function of the excitation frequency, and the polarization mechanisms exhibit a relaxation type behavior. Figure 39 shows the response of the real and imaginary part of the dielectric constant for a hypothetical wet material. The typical limiting frequencies for the various polarization effects, and the ionic and electronic resonances are shown on Figure 38. The specific relaxation response varies with frequency for various substances.

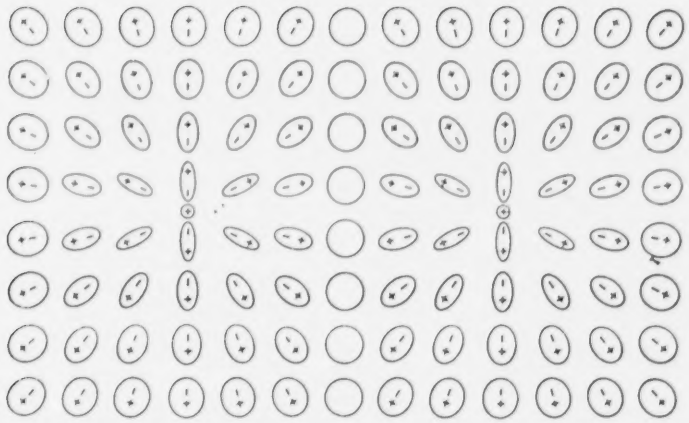


Figure 37. Polarization of the atom of a dielectric by a pair of positive charges, ⊕.

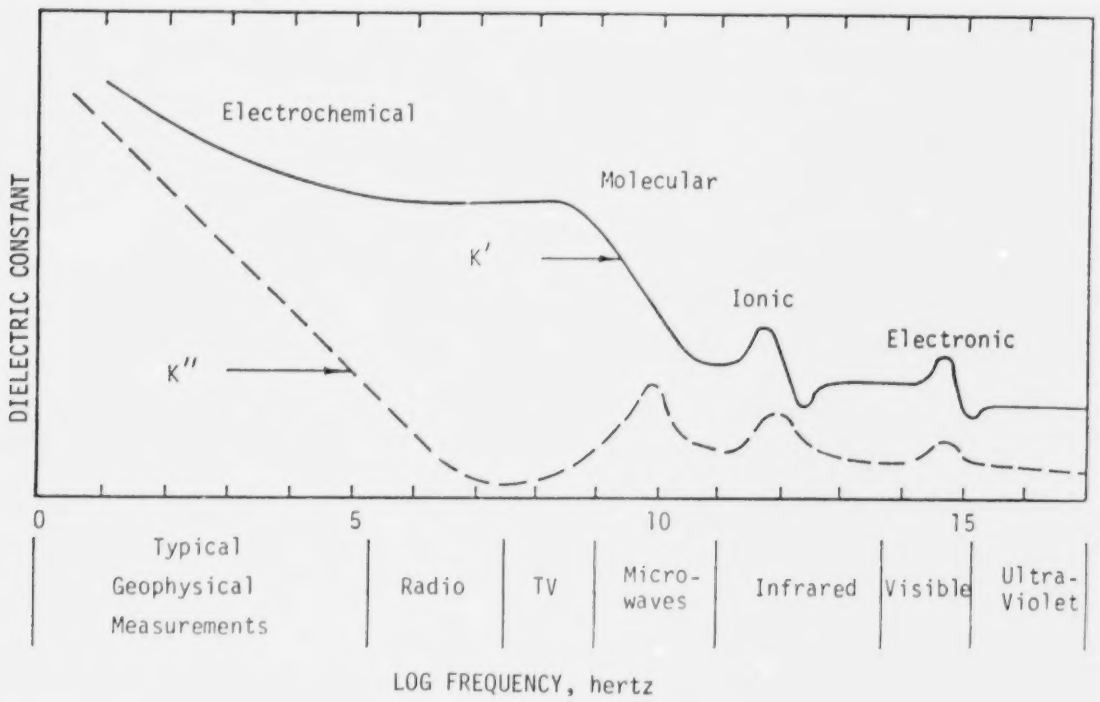


Figure 38. Real and imaginary part of the dielectric constant for a hypothetical wet material showing typical limiting frequencies for various polarization effects.

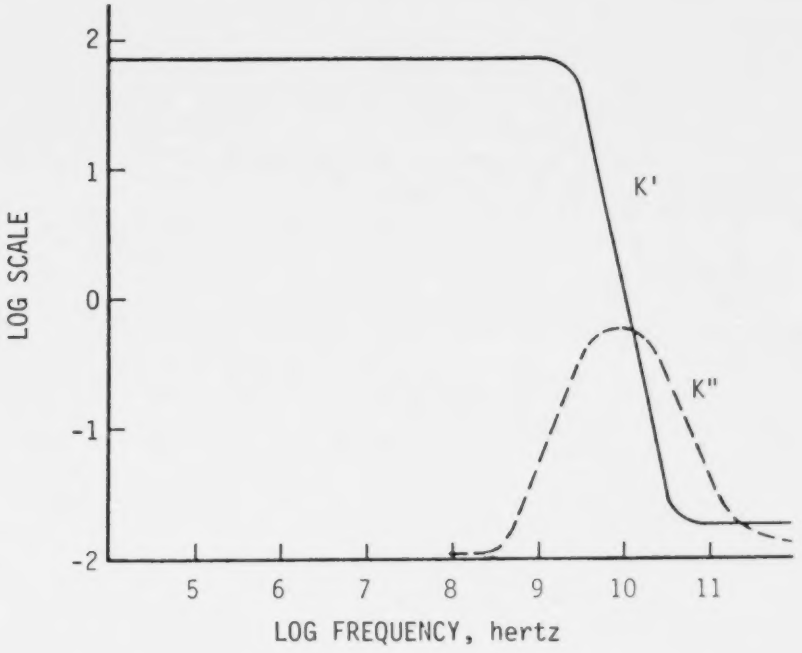


Figure 39. A typical relaxation response of the polar water molecule.

A relaxation type of polarization mechanism has a finite rate at which it can follow an excitation field. If the field varies much faster than this rate, the polarization mechanism becomes inactive. If the field varies at the response rate of the mechanism, the polarization follows the field but not perfectly. A result is that energy is dissipated in the material. If the field varies much more slowly than the mechanism response rate, the polarization tracks the excitation field very precisely and stores energy capacitively.

Dielectric materials are commonly used between the conducting plates of capacitors used in electronic equipment. The material between the conductors of commercially available transmission lines is also a dielectric material. Air is a dielectric material and all the dielectric properties of materials are described relative to air.

The above description of a dielectric material is a very simple generalization and many materials, such as crystals, and mixtures, such as wet soils, affect the field in a much more complicated manner. The above description, though, is a simple and useful starting point for generalization. Von Hippel [51] discusses various mechanisms in detail that affect relaxations. A typical relaxation response is exhibited by the polar water molecule as shown in Figure 39. Below 10 GHz, the water molecule will rotate sufficiently quickly to follow

the electric field. At frequencies higher than 10 GHz, the water molecule cannot rotate quickly enough to follow the electric field and the resultant dielectric constant is about 3. The dielectric constant of water below 10 GHz is about 80. At 10 GHz most of the energy in the electric field is lost in rotating the dipolar water molecule resulting in an increase in the dielectric loss term at this frequency.

Microwave ovens operate in the relaxation frequency range (1 to 10 GHz) of the water molecule to cook food. It is also interesting to note that the velocity of electromagnetic waves in the visible region at 10^{15} Hz in water is about 0.75 the velocity in free space whereas the velocity of electromagnetic waves at radio frequencies below 10^{9} Hz is 0.11 the velocity in free space. Note that the refractive index, n, is equal to the free space velocity of electromagnetic waves, c, (3×10^{8} m/s) divided by the actual velocity, v, in a medium and is also equal to the square root of the dielectric constant,

$$n = \frac{c}{v} = K^{1/2} \qquad 3.01$$

Dielectric Properties of Geologic Materials--

The electrical properties of geological materials are not simple. Typically in wet rocks and soils, complex electrochemical processes make the electrical properties very frequency dependent. Most electrochemical phenomena and Maxwell-Wagner effects have response times greater than 10^{-2} sec while molecular and atomic response times are less than 10^{-10} sec.

Recalling the electrical response of a wet material shown in Figure 38, it appears that over the frequency range of 1 MHz to 1 GHz, the real part of the dielectric constant is not strongly frequency dependent, and thus, it is unlikely that any strong relaxation mechanisms exist which would cause a strong temperature dependence on the real part of the dielectric constant, K'.

Figure 40 shows an expanded response of the complex dielectric constant versus frequency for a wet silty clay soil (Davis and Annan [11]). This curve is representative of the response observed in all soils and rocks [1, 17, 27, 34, 36, 41, 45]. There is evidence that often the dielectric loss, $K''(\omega) + \frac{\sigma}{\omega E_0}$ is less than the real part of the dielectric constant $K'(\omega)$, in the frequency range of 10^{7} to 10^{9} Hz [17, 34, 45]. The penetration range of a TDR system varies widely (10^{-1} to 10^{2} m) depending on the high frequency electrical properties of the material.

There are few data available in this frequency range where electrical measuring systems must be changed from those used by geophysicists below 1 mHz, to measure resistive or conductive properties, and from those used in the remote sensing field above 1 GHz, to primarily measure thermal properties in the microwave region. The higher frequencies do not have sufficient penetration in the ground for geophysicists, whereas the lower frequencies do have sufficient resolution.

The real dielectric constant over the frequency range of 1 MHz to 1 GHz for most dry geologic materials, including ice, lies between 1 and 10, whereas

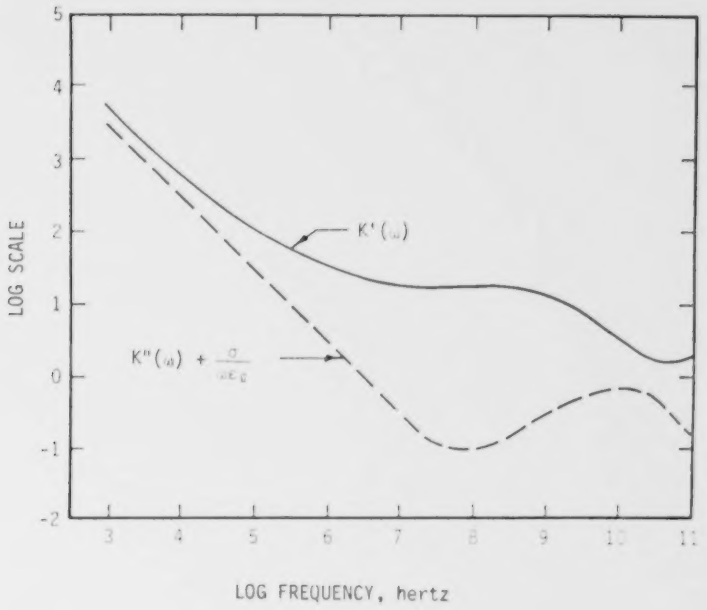


Figure 40. A response of the complex dielectric constant versus frequency for a wet soil.

the dielectric constant of water is about 80. Table I lists the electrical properties of a few common geologic materials. The dielectric constant, K', the propagation velocity, v, and the conductivity, σ, of the materials are shown. The conductivities of wet geologic materials vary widely depending on many factors such as free ion or impurity content and the way in which the fractures or pores are interconnected. Materials like clays tend to have electric charges on their platelets. Sea ice has complicated properties because of the brine channels changing the volumetric water content of the ice.

Sea ice and coal are materials that have anisotropic properties and thus the electrical properties vary depending on the polarization of the transverse electromagnetic wave [20, 10]. In coal the velocity remains about the same but the attenuation varies significantly with polarization.

We now have an idea about the high frequency electrical properties of geologic materials in general. The properties are dependent on many factors but over the frequency range of 10^6 to 10^9 Hz the dielectric properties do not vary very much with frequency, and the dielectric loss tends to be a minimum.

Dielectric Properties of Mixtures--

Soils are complex mixtures of solid mineral particles, water and air, and many experimenters discuss the electrical properties of heterogeneous materials in some detail [6, 15, 39, 42, 45, 50, 53, 54]). The solid mineral particles have

Table 1. ELECTRICAL PROPERTIES OF COMMON GEOLOGIC MATERIALS

Material	Propagation Velocity, v, (m/sec)	Dielectric Constant, K	Electrical Conductivity σ mhos/meter
Air	0.30	1	10^{-2} - 10^{-4}
Water	0.03	81	10^{0} - 10^{-1}
Ice	0.17	3.2	10^{-3} - 10^{-1}
Sea Ice	0.15 to 0.11	4 to 8	10^{0} - 10^{-2}
Dry Snow	0.21 to 0.17	2 to 3	10^{-5}
Wet Snow	0.15 to 0.09	4 to 12	10^{-3} - 10^{-4}
Dry Soils	0.17 to 0.12	3 to 6	10^{-4} - 10^{-5}
Wet Soils (>0 C)	0.12 to 0.05	6 to 40	10^{-1} - 10^{-3}
Wet Soils (<0 C)	0.17 to 0.07	3 to 20	10^{-2} - 10^{-4}
Rocks	0.15 to 0.09	4 to 12	10^{-2} - 10^{-5}
Granites	0.10	9	10^{-3} - 10^{-5}
Limestones	0.12	6	10^{-2} - 10^{-4}
Sandstones	0.15	4	10^{-2} - 10^{-5}
Dry salt (NaCl)	0.15	4	10^{-6}
Dry potash (KCl)	0.13	5	10^{-2} - 10^{-4}
Coal	0.12	6	10^{-1} - 10^{-3}

Note: The dielectric constant of wet geological materials is strongly dependent on the volumetric water content and only weakly dependent on type of material, texture, temperature and density. (Topp, et al., 1980).

dielectric constants that lie between 2 and 9 depending on the material and the density. Air has a dielectric constant of 1 and free water has a dielectric constant of 80. Free water is mentioned because it has been noted that tightly bound water molecules usually found at the surface of soil particles have a dielectric constant approaching 3, similar to that of ice. Thus the surface area of the soil mixture is likely to have an effect on the electrical properties of soils, especially fine grained soils or clays. The particle shapes and orientations can also affect the bulk dielectric constant of the mixture.

Topp, Davis and Annan [45] have shown empirically that the dielectric constant is strongly dependent on the volumetric water content of soils and almost independent of soil texture, density and temperature and fluid conductivity. Figure 41 shows a typical response that Topp, et al., found using soils having widely varying textures such as sandy loam and silty clay soils. The relationship of the apparent dielectric constant, K_α to the volumetric water content, θ_v, is given by

$$K_\alpha = 3.03 + 9.3\theta_v + 146.0\ \theta_v^2 - 76.7\theta_v^3. \qquad 3.02$$

The standard error of estimates of θ_v from K_α is 0.013 or 1.3 percent over the complete range of water contents. Usually K_α is measured and then θ_v is determined by using the following equation.

$$\theta_v = -\ 5.3 \times 10^{-2} + 2.9 \times 10^{-2} K_\alpha - 5.5 \times 10^{-4} K_\alpha^2 + 4.3 \times 10^{-6} K_\alpha^3. \qquad 3.03$$

It was also noted by Topp, et al., that the relationship was acceptable for various sizes (30 μm and 400 μm) of glass beads, an organic soil, vermiculite, and even wet snow samples and these results are shown in Figure 42.

There is further evidence from a wide range of electrical measurements in the frequency range of 1 MHz to 1 GHz, to show that there is a very strong relationship between the high frequency dielectric constant and volumetric water content in soils as shown in Figure 41 [8, 22, 23, 26, 32, 33, 44, 45]. The fact that data, of six experimenters using widely differing measuring techniques and soils, agree so well is indicative that a strong and basic relationship between the apparent dielectric constant and volumetric water content in wet soils does exist.

The above relationship apparently is also valid for determining the unfrozen water content in fine grain soils at temperatures below 0°C according to Patterson and Smith [38]. The dielectric constant of ice is about 3 at frequencies between 10^6 and 10^9 Hz and thus similar to the dielectric constant of soil mineral particles. It is interesting to note that the relaxation frequency of ice is around 10^4 Hz and thus the high frequency electrical properties are not affected by the relaxation mechanisms of the solid nor the liquid phase of the water molecule.

This strong relationship between the dielectric constant, at frequencies between 10^6 and 10^9 Hz, and the volumetric water content of wet granular mixtures allows us to measure a soil physical property which is primarily a function of water content and that does not need to be inferred. Thus it may be reported that one experimenter has observed reflections at ranges of 10 to

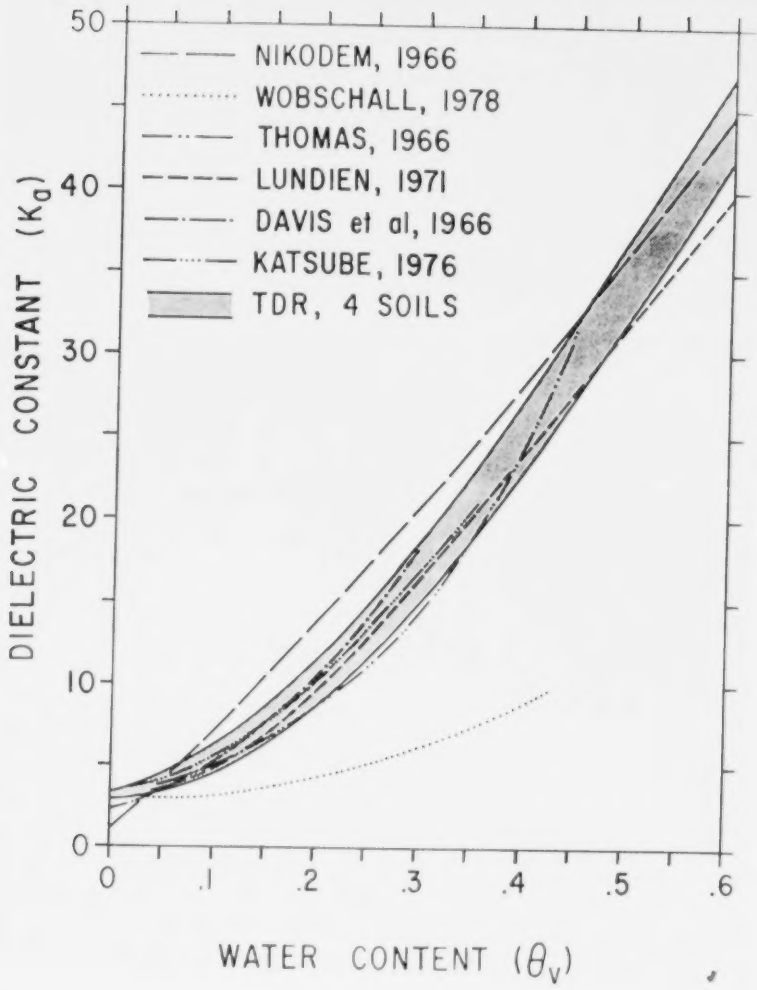


Figure 41. A comparison of results of K_a versus θ_v from six different experiments using a wide variety of measuring techniques, over the frequency range of 10^6 to 10^9 Hz, and soil types. (From Topp, et al. [45])

100 m in one coal seam, whereas in another seam the penetration ranges were only 1 to 10 m (personal communication, J.C. Fowler). This large variability makes it impossible to state the range of a TDR system in a medium until electrical measurements at high frequencies have been carried out.

Wet soils are another example where the electrical loss can vary widely. It is often thought that as the water content increases the electrical loss increases. This is often the case but if the water is fresh and the conductivity

remains low then penetration ranges of much more than 10 m is possible; thus the high frequency loss properties of the material is the factor from which the maximum penetration range is determined.

Summary--

This section has introduced us to what a dielectric material consists of and many different aspects concerning the high frequency electrical properties of geologic materials. A point that stands out in this section is the complexity of the electrical properties primarily due to the complexity of the geologic materials that we are dealing with. Over the frequency range of 10^6 to 10^9 Hz the dielectric constant is not strongly frequency dependent and that the electrical loss also tends to be a minimum; thus the signal propagation velocity is likely to be independent of temperature and the penetration range will be a maximum. Topp et al. [45] show comparative high frequency dielectric measurements with the TDR data that indicate that the real part of the dielectric constant in soils is strongly dependent on the volumetric water content and only weakly dependent on the soil type, soil density, soil temperature and soluble salt content. The dielectric loss which affects the signal penetration range is affected by the soil density, soil temperature and soluble salt content and the range in soils varies over a wide range. The range in other materials also varies over a wide range depending on the conductivity of the material and also the manner in which the conductive channels are interconnected.

There are no easy answers when one considers the many variables of all the complex geologic media. Fortunately we can carry out meaningful high-frequency electrical measurements and time-domain reflectometry, TDR, is a wide-band technique that can be used to determine the electrical properties of materials over the frequency range of 10^6 to 10^9 Hz. The wide band characteristic of TDR gives it the capability of carrying out high-resolution measurements in geologic materials. It can be used in the field and as such is potentially a powerful tool for measuring the high-frequency electrical properties of geologic materials.

Overview - Transmission Lines

The TDR equipment is coupled to the geologic medium by a transmission line. In fact the geologic medium becomes a significant part of the transmission line and has a major effect on the electrical characteristics of the line. A transmission line consists of two conductors and a material around and between the conductors, which in this case is the geologic material to be measured.

Transmission Line Principles--

It is useful for potential users of TDR to understand some of the fundamental concepts of transmission line principles. There are available a multitude of texts for physics and electronic engineering students dealing with transmission line principles. It is not the intent here of repeating in detail that which is well documented, but we feel that it may be worthwhile to mention at least some of the basic concepts for potential users with little or no electronic background. Texts offer useful and varied discussions on transmission lines [5, 21, 24, 25, 30, 40].

A transmission line consists of a conducting medium, the two conductors, and a dielectric medium which occupies the space between and around the conductors. Figure 42 shows a very general representation of a transmission line. The conducting media in this case are two parallel plates separated from one another in air which then becomes the dielectric medium. The line is shown with an oscillating source connected at one side of the conductors and a load impedance, Z_L, connected on the opposite side of the conductors. The currents in the two conductors are equal and opposite in direction at every instant at any cross section and the energy is transmitted along the line primarily by the electric and magnetic fields in the dielectric. The conductors merely act as guides to the fields.

The two plates have equal and opposite charges on them at any instant in time and thus an electric field is set up between the plates in a direction perpendicular to the plates as shown by the vector $\bar{E}_{\hat{x}}$ on Figure 42. Since there are currents flowing from the source to the load in the Z direction along the conductors there will also be a magnetic field which is mutually perpendicular to the direction of propagation and the electric field, as shown by $H_{\hat{y}}$. This type of wave which has an electric and magnetic field at right angles to the direction of travel is called a transverse electromagnetic (TEM) wave and has exactly the same characteristics as an unbound TEM wave in free space.

The two conductors may take on several forms, which may be broadly divided into balanced and unbalanced lines. Two identical wires symmetrically placed with respect to a ground plane or inside a tubular conductor are representative of balanced transmission lines, while one conductor with a ground return, or at the center of a conducting tube are representative of unbalanced lines. Figure 43 shows schematically the different types of transmission lines. The electric field (solid) and magnetic field (dashed) are also shown.

The type of line shown in Figure 43 (a) is sometimes called an open-wire line and usually we refer to this line as a balanced parallel transmission line. Figure 43 (b) is known as a screened pair, while that in (c) is known as a single-core line with a ground return or in microwave engineering as a strip line and is commonly used in printed circuits, and (d) shows a coaxial transmission line. If the outer conductors of lines (b) and (d) are perfect there will be no external fields.

There are a large number of specific transmission line configurations that may be advantageous in different practical applications. It is impractical to discuss each configuration and especially since they all conform to the same principles. The next section discusses three types of common transmission lines.

Transmission Line Types--

Different transmission line types that may be used to carry out electrical measurements using TDR are briefly discussed below presenting some of the practical aspects of the major line types and their advantages and disadvantages.

Coaxial transmission lines--The coaxial type of transmission line is one in which all the electric field passes through a known volume of material in the line. The electrical measurements in the coaxial line are isolated from the

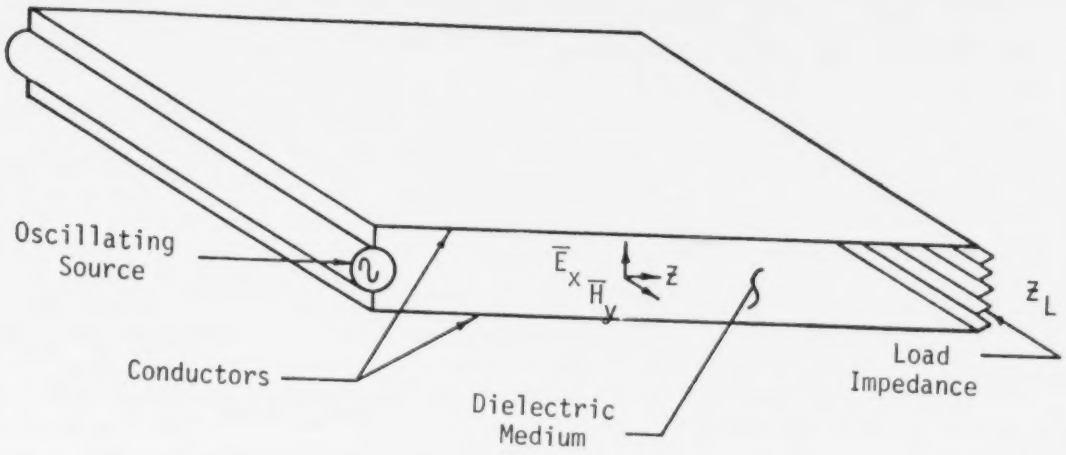


Figure 42. A general representation of a transmission line. The conductors are two parallel plates separated from one another in air, which is the dielectric medium.

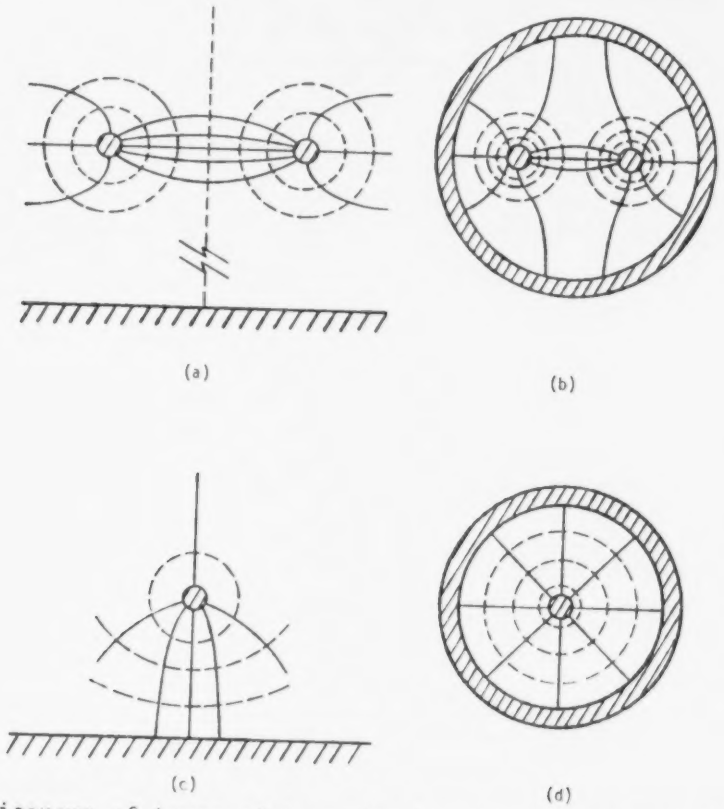


Figure 43. Diagrams of types of transmission lines: (a) and (b) are balanced and (c) and (d) are unbalanced. The solid lines represent the electric field and the dashed lines the magnetic field.

surroundings and therefore are often ideal for laboratory measurements. If we have a core specimen from a borehole to be measured then a hole down the center of the core must be drilled for the center rod.

Topp et al. [45] show a coaxial transmission line they used to measure the dielectric constant in soils. The coaxial tubes they used were about 5 cm inside diameter and either 1 or 0.3 m long. Their tube had holes with porous ceramic disks in them along two sides of the coaxial tube. These holes allowed water to be put in and taken out of the soil without disturbing the soil specimen.

A coaxial-type hand probe for field use has also been constructed and used. The outer conductor was 20 cm long and had a diameter of 5 cm and was designed in the form of a soil corer. The inner conductor had a diameter of about 0.5 cm. This hand probe was designed for field use, so that the electrical measurements could be compared to volumetric water content measurements by drying a known volume of soil and comparing the wet and dry weights of the soil. The coaxial probe was difficult to insert in the ground and there was often soil compaction when the probe was hammered into the ground.

Coaxial transmission lines do not lend themselves well to field monitoring of changes of electrical properties versus time. Clearly an open wire line is better for monitoring changes in the ground since there is less disturbance to the medium.

Parallel transmission lines--Many different types and geometries of parallel balanced transmission lines have been used in the field and the laboratory. Transmission line lengths from 5 cm to over 6 m, with conductor spacings varying from 1 cm to 2 m, and rod diameters varying from 1 mm to 5 cm have been discussed in the literature and were used for a wide variety of applications.

Davis (1975), Topp and Davis (1981), Topp et al. (1982(b)) [9, 46, 49] have described different types of balanced-parallel wire transmission lines that they used in the field. Generally their transmission lines were made of 13 mm brass rods 1 m long with a center-to-center spacing of 5 cm. These dimensions were chosen as a compromise between ease of field installation, volume of soil sampled, and depth resolution of the measurement. They also used transmission lines with markers at known locations along the line. The markers were made by reducing the diameter of the rods from 1.3 cm to 1.0 cm, for lengths varying from 4 to 20 cm depending on soil loss properties and depth of the marker in the ground. They recommend that these gaps be filled with a high dielectric (K = 12 or 16) material to reduce the effects of the resulting air gap.

A further point regarding the use of transmission lines with markers is that a simple line installation can be made and a profile of dielectric constant versus depth can be obtained between the markers or from the surface to each of the markers. Installations, equal to the number of markers, of vertical transmission lines without markers are necessary to obtain the equivalent profile. The horizontal variability in the soil will increase the uncertainty or variances of the measured dielectric constant versus depth if different trans-

mission line lengths are used. In practice, though, it is often difficult to detect the line discontinuities. The amplitude of the signal reflected from these discontinuities typically ranges up to 10 percent of the incident signal amplitude, whereas all of the signal reaching an open or short circuit at the end of a transmission line is reflected. As the attenuation of the TDR pulse along the line increases, the amplitude of the reflections decreases and may not have sufficient amplitude to be detected at the receiver. This point must be kept in mind when designing transmission lines with discontinuities. We do not want too much of the pulse to be reflected and therefore we do not want too large an impedance change, but in lossy soils the length of the discontinuity must be long enough so that the pulse with a long pulse-rise time reaches its maximum amplitude. Clearly we need to have some estimate of the dielectric loss in the material we wish to measure.

Topp and Davis [47] mention that they used 40-cm-long transmission lines with wires 1.6 mm in diameter pushed horizontally into the soil at different depths from pits. The connecting cables were brought to the surface level and the pit was backfilled. These horizontal lines seem to give very satisfactory electrical property data at the different depth, and it was suggested by the experimenters the reason is due to the larger measurement volume at a particular depth decreasing the effects of soil variability in the horizontal plane. A practical problem with these lines is that the connecting cables break away from the parallel balanced transmission lines if the ground freezes, especially in fine-grained soils.

Topp and Davis (unpublished) have also developed a hand-held parallel-balanced transmission line probe that is used to make rapid measurements in the near surface of the soil. The transmission line is made of conically shaped stainless steel rods of different lengths, varying from 10 to 30 cm, depending upon the specific requirements. The rods are spaced 5 cm apart. The conical shape of the rods helps to ensure that air gaps are kept to a minimum and also helps reduce the friction when removing the probe from the soil.

The reader can see that there are many different possible types and arrangements of transmission lines that can be used both in the laboratory and the field. There are many applications where we would prefer to have the electric field radiate out from the transmission line so that a maximum volume of material is sampled by the transmission line. J.L. Davis is working on several designs, but further experiments are needed to determine the practical usefulness of these designs. Fringe effect lines discussed next are sometimes used because they appear to have some practical value but electrically they have very limited use.

Fringe effect lines--A third type of transmission line sometimes used will be placed under the general heading of fringe effect lines. These lines do not have the medium that is to be measured between the conductors of the transmission line. The medium is outside the area of the conductors. An example of this type of line would be the use of commercially manufactured 300 ohm twin leads, often used to connect TV antennas to the television set. These ribbon type transmission lines are readily available and inexpensive. This type of line may be very satisfactory if measurements to show only that the dielectric constant has changed from a low to a high dielectric constant or vice versa are

needed. Figure 44 shows a typical response in a 300 ohm TV ribbon line of the actual dielectric constant around the line to the measured dielectric constant in the line. The dashed line, at a slope of 1, is that of an open wire transmission line discussed earlier. If the ON/OFF response of the ribbon line is satisfactory then a significant advantage of this type of line when used in a lossy medium is that the loss of the medium around the ribbon line has little effect on the signal propagating in the line. Therefore, long line lengths may be put in the ground but at the cost of very limited change of dielectric constant response. The volume of soil sampled using this type of line is also very small as will be shown later.

There are other examples of fringe effect types of transmission lines where the conductors are put into the circumference of a plastic tube and the effect of the changing dielectric constant around the tube changes the measured apparent dielectric constant slightly, but most of the electric field is either in the plastic tube or just in the soil around the tube. Again if the limited dielectric constant response is satisfactory for the specific application then drilling one hole in the ground rather than two is definitely a significant practical advantage.

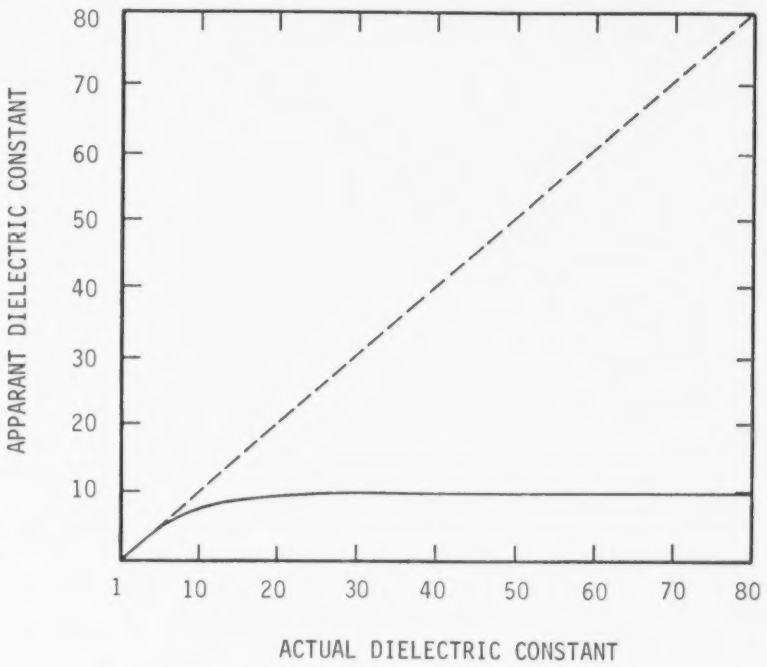


Figure 44. The actual dielectric constant response versus the measured dielectric constant of a 300 ohm ribbon type transmission line. The dashed line is the response of an open wire line which gives a 1:1 response.

Davis has also experimented with a monopole type of antenna placed vertically in the soil. The monopole antenna has one rod placed into the soil and a mesh acting as a ground plane placed on the ground surface. The initial measurements gave very promising results but further work is necessary to determine the volume of soil affecting the measurement. The monopole antenna offers the possibility of only having to place one conductor into the ground.

TDR Measurement Volume--

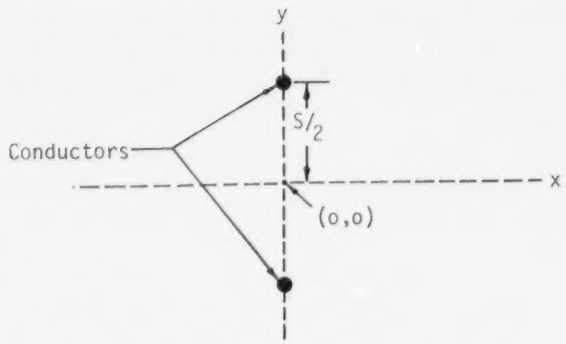
One further point must be noted here, especially when making field measurements of water content using TDR, and that is soil variability. We usually are measuring the change of water content with depth in the soil and wish to assume that the measurements represent a large area in the horizontal plane. However, the soil can vary significantly in the horizontal plane. The measurement area of a parallel wire transmission line is approximately a rectangle when sides are 1.5 times the line spacing by the line spacing. This estimate is only rough and varies depending on the electrical properties of the material around the TDR transmission line. Recall also Figure 43 showing the electrical field lines in a parallel wire transmission line and note that most of the electric field lines lie between the conductors and the density of the field lines decrease as we move out from the center of the conductors as shown diagramatically in Figure 45. Figure 45 (a) is a plan view of the conductors and we are looking from one end. Figure 45 (b) shows how the flux density, D, varies with distance along a line originating at the center point between the conductors and running perpendicular to the line between the conductors as shown in (a). Note that the flux density is a maximum at the center point between the conductors and decreases as we move out away from the center as shown. The same relationship is true as we go along the native x axis. Along the y axis the flux density will be constant out to the conductor then go to zero through the conductor and decrease exponentially as y increases as shown in Figure 45 (c). Thus most of the electric fields are between the conductors.

Note further that an ellipse whose focii are the conductors might be a better representation of the area of the field but a rectangle does not add significantly to the error of estimating the area of the majority of the field. Thus for a parallel wire line whose conductors are 5 cm apart, the area of measurement is about 37.5 cm^2. This is a very small measurement area especially if we expect it to represent areas of hundreds of square meters!

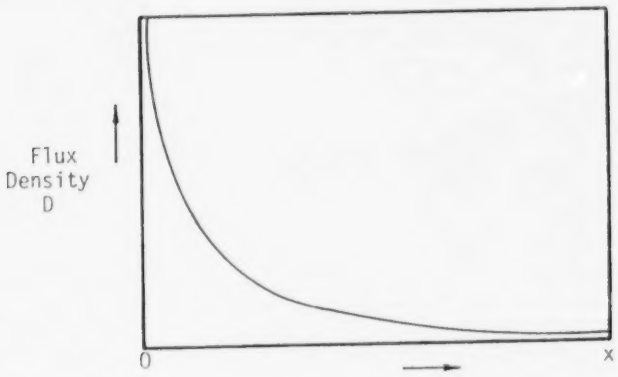
Summary--

A transmission line is made up of two conductors and a dielectric medium between and around the conductors. The energy propagates primarily in the dielectric medium and the conductors act as guides to the fields. The wave that propagates in the dielectric is called a transverse electromagnetic TEM wave and it has the same characteristics as a TEM wave propagating in free space.

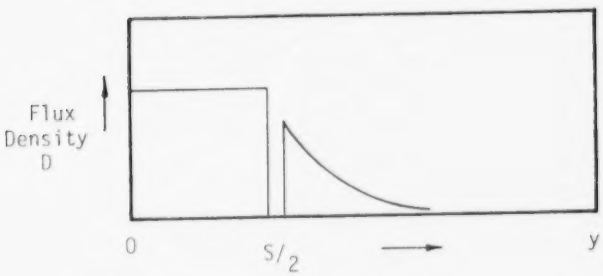
There are many different configurations that transmission lines may take but they are broadly divided into balanced and unbalanced lines depending on the symmetry of the line with respect to the electrical ground.



(a) End view of conductors.



(b) Distance from center of conductors.



(c)

Figure 45. Electric flux density around the conductors of a parallel transmission line. In (b) the flux density is shown along a line originating at the center point (o,o) between the conductors and running along the x-axis. In (c) the flux density is shown along a line originating at (o,o) and going along the y-axis.

It was pointed out that coaxial transmission lines in which we know the volume of the fields are possibly best suited for laboratory experiments. Balanced parallel transmission lines, which do not disturb the material in which they are being placed as severely as coaxial lines, are best suited for field measurements and especially for monitoring changes of electrical properties over time. Great care is necessary to eliminate any air gap around or between the conductors but the installation techniques do not critically affect the electrical measurements. It seems that rods pushed into slightly undersized pilot holes would disturb the soil between the conductors the least. Fringe effect lines are not satisfactory for measuring the dielectric constant over a wide range but offer a HIGH/LOW warning capability. These lines also do not sample a large column of material around the lines.

Now we shall discuss the time-domain reflectometer equipment and then how a TDR and a transmission line placed in geologic material can measure the high frequency electrical properties materials.

Overview - TDR Equipment

Introduction--

Time-domain reflectometry is a wide-frequency bandwidth technique used to measure the electrical characteristics of transmission lines. TDR has usually been used by communications engineers to look for faults in transmission lines which are approaching ideal electrically or are low loss and long. Distance resolution for a few centimeters and accurate amplitude measurements of reflections of up to one ten thousandth (-80 dB) the amplitude of the source signal is achieved in practice. For this study, we are interested in TDR's capability for measuring the electrical properties of geologic materials in transmission lines in which the spacing between the conductors is relatively large (i.e. the material becomes a significant part of the transmission line). Figure 46 shows a block diagram of a TDR showing the main components. We shall discuss how a time-domain reflectometer works: more specifically how the receiver and the pulser work and how they are coupled to the transmission line under test. We shall see what the general characteristics of the TDR output trace looks like and what the data trace represents electrically and physically. We shall also learn about the frequency content of the time domain signal used in TDR's and the relationship between the frequency domain and the time domain.

Equipment Operation--

A time-domain reflectometer is much like a one dimensional radar in which the signal is confined to the transmission line under test. The TDR consists of five major sections as shown in Figure 46. The TDR has a timing control unit which synchronizes all the timing for the pulser, the receiver, the data recording and, the data display. The pulser generates a wide frequency bandwidth pulse which travels through the sampling receiver to the transmission line under test. Reflections from the transmission line are also detected by the sampling receiver which puts out a low frequency facsimile of the high frequency input. The receiver output is then processed, displayed, and recorded depending upon the user's requirements.

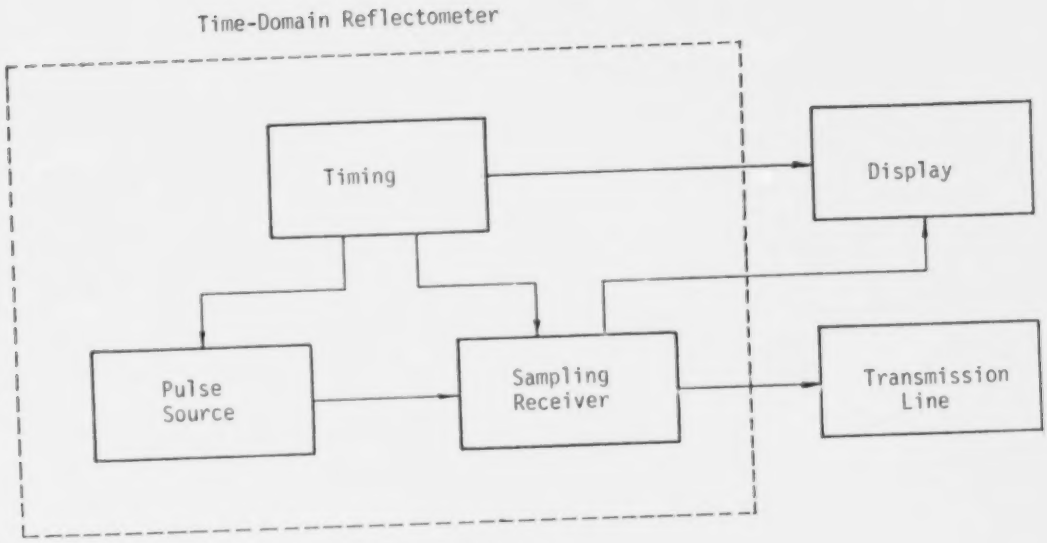


Figure 46. A block diagram of a TDR system showing the main components.

The operational concept is quite simple to understand, though most of the equipment, especially the radio frequency aspects, are complicated. The low frequency output is easy to use. The most complex and critical part of the TDR is the sampling receiver.

Receiver--The sampling receiver puts out a lower frequency facsimile of the high frequency input. Fundamentally the sampling principle is analogous to the principle of optical stroboscopes. A stroboscope generates very brief flashes of light which, when properly timed, can make rapidly moving things appear to be at rest or occurring in slow motion. Instead of generating flashes of light, sampling receivers generate very short electrical pulses which allow us to "look" at a repetitive signal one point at a time and reproduce the signal slowly over a period of many cycles. The length of the electrical pulses determines the maximum frequencies that can be observed, which is typically on the order of 1 to 10 GHz.

In the sampling technique it is important to remember that the high frequency waveform must be repetitive while a sampled low frequency scan is being constructed. Figure 47 shows a high frequency sine wave and the sampled low frequency facsimile. There are usually many more samples used to reconstruct the high frequency waveform precisely than are shown in Figure 47 (only a few samples per sampled output are presented on the diagram for clarity). In TDR the sampling time is kept constant and the sample point is moved out at a fixed time increment each time the TDR pulser fires. This allows the sampler to construct an amplitude versus time scan.

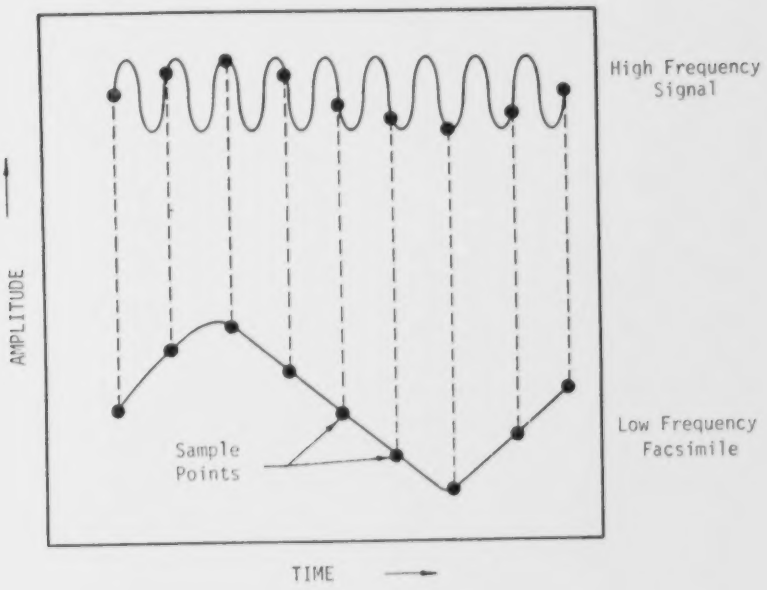


Figure 47. The sampled low frequency output of a repetitive high-frequency input signal.

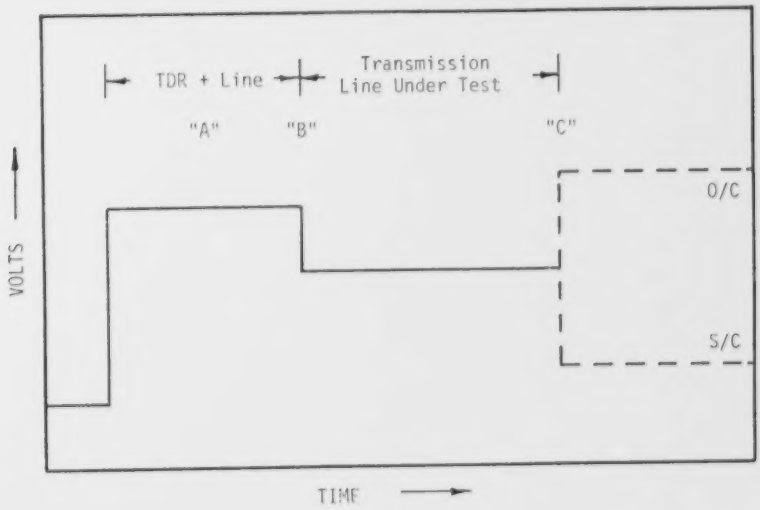


Figure 48. An idealized TDR data response. "A" represents the TDR unit, "B" represents the location where the TDR is connected to a transmission line, and "C" is the end of the transmission line, which may be either an open circuit, O/C, or a short circuit, S/C.

The low frequency facsimile of the high frequency TDR trace can then be either photographed, recorded on an analog audio frequency tape recorder, or digitized and processed. The fact that the low frequency facsimile output of the TDR signal is in the audio-frequency range with an upper frequency seldom greater than 1,000 Hz in practice, and often only in the range of a few hertz, permits us to easily process and store the data. The data can also be obtained every few seconds if repeated measurements are necessary. The data can be transmitted along telephone lines, telemetry links, or through satellites. This makes time-domain reflectometry a very attractive remote monitoring technique where variations in electrical properties need to be measured.

Pulser--The TDR pulser produces a fast rise-time step function. This is done by switching a diode, typically a tunnel diode, from the OFF state to the ON state, thus allowing a voltage to be put on the transmission line. The transition time for the voltage to go from the OFF state to the ON state varies typically from between 10 ps to 10 ns. The switching rate determines the upper frequency limit of the step function and thus determines the maximum resolution of the TDR. The frequency content of typical TDR pulses is 10^5 to 3×10^9 Hz. The step generated pulse is put through the sampling receiver and then onto the transmission line under test.

TDR Data Trace--

The step function is generated repeatedly about once every 10 μs and a full trace is obtained on the oscilloscope at rates up to once every 20 ms thus producing at least 2,000 data points per scan. On most displays the trace appears as a continuous line rather than the many dots which in fact the trace is made up of.

The voltage step from the source travels through the sampling receiver, and then to the transmission line under test. Figure 48 shows an idealized TDR response. The letters "A", "B" and "C" shown on Figure 48 indicate the position in the TDR equipment where the trace relates. Before "A" the diode switches and a voltage is applied to the transmission line. Since the transmission line from the signal generator through the sampling receiver and to the transmission line under test has a well matched impedance (50 ohms) no reflections are observed in region "A". On entering the transmission line in the geologic material part of the signal is reflected and part of the signal enters the line because the impedance of the transmission line under test is usually different compared to the impedance of the TDR equipment. Thus at "B" on the TDR response, there is a change in the voltage proportional to the magnitude of this reflection. The signal that enters the transmission line under test propagates through the line until it gets to the end of the transmission line, "C", where in this example it sees either an open circuit, o/c, or a short circuit, s/c. Ideally all of the power is reflected at a perfect open or short circuit. In practice some of the signal may be radiated from an open circuit of a transmission line.

There are a number of commercially available TDR units at present manufactured by Tektronix and Hewlett-Packard. Both companies have high quality laboratory instruments with step-pulse rise times of 30 ps. Tektronix makes two field portable cable tester units, one with a step pulse rise time of 100 ps and the other with a half sine wave source. The pulse widths on this second unit can be set to 10 ns, 100 ns and 1,000 ns. This unit is only useful

if the transmission line lengths are very long. There is a company, Foundation Instruments, in Ottawa, Ontario, under license from the Canadian government, that is designing a TDR system especially for use in carrying out soil water content measurements.

The commercially available TDR's usually have sampling receivers with sensitivities on the order of 2×10^{-3}V and step pulse amplitudes ranging between 0.1 to 0.5 volts; thus they have a transmit voltage to receiver sensitivity voltage between 26 dB and 54 dB, with most units being around 40 dB. Oliver (1964) states that systems having 80 dB sensitivity, such that reflection coefficients on the order of 10^{-4} could be detected, were in existence at that time. Existing data analysis such as averaging and correlation techniques can also help improve the signal-to-noise ratio and thus the TDR sensitivity.

The units can measure the signal travel time to an accuracy of 2 percent or better. Normally the TDR's have a precision that is significantly better than 2 percent and calibration lines can be constructed to obtain better accuracy. Lower resolution but higher signal power TDR may be necessary for detecting leaks under waste impoundment sites.

Summary--

In this section we discussed how a time-domain reflectometer works. A TDR consists of a timing unit to control first, the step signal pulse generator; second the sampling type receiver which produces a low frequency, less than 1 KHz, facsimile output of the high frequency, greater than 100 KHz TDR input signal; and third the data display unit. We described the form and significance of the TDR output trace.

Commercially available TDR units generate step pulses whose rise times are equal to or less than 100 ps; thus they have bandwidths of 3 GHz or more. The primary high frequency limits are not due to the equipment but due to the losses in geologic materials. Thus, the resolution of a TDR when used in geologic materials is primarily dependent on the high frequency electrical properties of the material being tested. Further discussions on this will come in the next section which relates the electrical properties of geologic materials with the measurement capabilities of a TDR.

Commercially available TDR units can detect reflected signal voltages that are about 40 to 60 dB, (10^{-2} to 10^{-3}), down on the incident signal. The range along a transmission line is dependent upon the sensitivity of the equipment and an increase of sensitivity may increase the penetration range. The attenuation of the TDR signal is dependent on the electrical loss properties in geologic materials which are very complex.

Conclusions

This review has given evidence based on published papers to show that TDR is a useful technique for carrying out high frequency, 10^6 to 10^9 Hz, electrical property measurements in geologic materials. Most of the examples offered relate to using the TDR technique to make volumetric soil water content measurements. This is because the electrical properties of water are

very different, about 20 times greater than those of dry soils, and thus the electrical properties of wet soils vary primarily due to the water content. Water content measurements, from a practical aspect, are becoming increasingly important as the cost of water is increasing around the world.

The TDR technique can make rapid volumentric water content measurements in soil, or the technique can easily monitor changes of soil water contents over long periods of time. The volumetric water content can be measured to $\pm$1.3 percent using the TDR technique. In the field the TDR technique can measure volumetric water contents to the same accuracy, $\pm$2 percent, as gravimetric measurements. The technique can easily measure water content profiles versus depth in the soil if markers are put on transmission lines at known locations. The TDR technique can also measure the distance to a wetting front or a freezing front. Examples are referred to showing that the TDR can determine these fronts typically to within 5 cm at ranges up to 1 m.

TDR equipment exists at present that can be used to make electrical property measurements in the laboratory and in the field. Equipment development is being carried out to simplify the measurements and the data interpretation. The equipment has potential for carrying out automatic measurements in remote areas.

The TDR technique can make high resolution measurements, both from an electrical property and spatial aspect. The electrical properties of geologic materials are complex and may vary widely from location to location, both on the horizontal and vertical axis. It happens that over the frequency range of most TDR's, 10^6 to 10^9 Hz, the electrical properties of geologic materials appear to be almost independent of frequency and the electrical loss properties appear to pass through a minimum. This indicates that the measurements should be almost insensitive to temperature variations in wet materials and that the signal penetration range should be a maximum compared to other systems using either higher or lower frequencies. Even having these good properties the TDR data is complex and a great deal of experience related to the electrical properties of the material being measured and experience related to the equipment is necessary in order to obtain maximum advantage of the technique.

The TDR technique has great potential for measuring the electrical properties of materials and for monitoring for changes of electrical properties with time.

OVERVIEW OF LABORATORY STUDIES

The objective of this study was to determine the size of an anomaly (simulating a leachate) that can be detected as the transmission line conductor spacing is varied. The experiments were divided into two parts: (1) Measuring the rise time of the reflection from an open circuit transmission line as the conductor spacing was increased, and (2) determining the physical size of an anomaly that had a velocity contrast of 2:1 compared with the host medium (air) as the transmission line conductor spacing was varied.

The review of the TDR method has shown us that the technique is very versatile and can be used in a wide variety of ways to measure the electrical properties of soils in a transmission line. If the electrical properties of the leachate are different from the electrical properties of the soil outside of a liner, then the TDR technique will detect the presence and extent of the leachate in the transmission line. A number of factors affect the TDR measurement of electrical variations along a transmission line. Some of the more important factors that affect the TDR measurement of electrical variations along a transmission line are:

(1) The magnitude of the change of electrical properties of the anomaly compared to the host material along the line,

(2) The physical dimension of the anomaly in the transmission line,

(3) The electrical loss properties of the host material in the line,

(4) The number of anomalies along the transmission line,

(5) The source power and receiver sensitivity of the TDR electronics,

(6) The pulse length of the TDR pulse or the pulse rise time in the case of a step pulse, and

(7) The spacing of transmission line conductors.

The first four factors listed are related to the electrical properties of the materials and the last three factors are related to the TDR equipment. We shall briefly discuss each of the factors.

(1) Part of the TDR pulse is reflected and part of the pulse continues on at each change of electrical properties of the material in the transmission line. The greater the change of electrical properties the greater the amplitude of the incident TDR pulse signal reflected at the interface. Therefore more signal is returned to the receiver the greater the electrical contrast of the anomaly in the transmission line.

The electrical properties of the soil under a waste impoundment liner may vary widely but the TDR pulse will have a propagation velocity between 0.3 and 0.4 the velocity of the pulse in air which is 3×10^8 m/s. The dielectric constant, K, is inversely related to the signal propagation velocity, V, in a medium as shown by the following relationship:

$$K = \left[\frac{c}{V}\right]^2$$

where c is the propagation velocity of the wave in air and is equal to 3×10^8 m/s. Thus, the dielectric constant increases as the signal propagation velocity in the medium decreases.

The propagation velocity of a TDR pulse in a leachate saturated soil will probably be between 0.15 and 0.2 that of the velocity in air. The propagation velocity of the signal in moist soil having a volumetric water content of up to 20 percent will be 0.3 to 0.5 the velocity in air. Thus, we can expect a velocity variation of about 2 between the host soil and the leachate saturated soil. About 30 to 40 percent of the incident signal will be reflected at the electrical contrast discussed. TDR systems can easily measure reflected signals that are about 5 percent the incident signal amplitude. More studies are necessary to determine the electrical properties of leachate saturated soils.

(2) The previous discussion assumed that the anomaly was physically much larger in extent along the transmission line compared to the electrical length of the TDR pulse. As the size of the anomaly becomes smaller compared to the pulse length in the medium, the amplitude of the reflected pulse decreases. TDR units using step pulses can resolve layers that are about 1 cm thick. The TDR units using an impulsive type pulse have poorer resolutions that vary with the pulse length: some only have resolutions on the order of meters. These impulse systems have the advantage of much greater signal powers than the step pulse systems.

We need to determine the physical dimensions of electrical anomalies in the transmission that a TDR unit whose pulse properties are known can detect. This is one of the objectives of this project.

(3) The electrical loss properties of the host material determines the pulse amplitude along the transmission line. If the electrical losses of the host material are high then much of the pulse power will be lost as it travels along a short length of transmission line. If, on the other hand, the loss properties of the material in the line are low then the pulse amplitude will decrease very slowly and the signal will travel over very long lengths of transmission lines. Coarse grained soils like sand and gravel generally have low electrical loss properties and thus signals travel over long distances with little decrease of the pulse amplitude. The opposite is generally true for fine grained soils such as clays. Soils that have electrically conductive liquids in its pores also attenuate TDR signals very rapidly. Many leachate materials are likely to be electrically conductive compared to the liquid in the host soil material. Again the electrical properties of leachate materials need to be studied. In this project we modeled a host material and anomalies that were resistive and not conductive.

(4) As the number of anomalies along a transmission line increases the loss of incident signal power at each successive anomaly increases. Recall that part of the incident signal is reflected and part of the signal continues on at each electrical contrast in the transmission line. Thus, it is important to keep the electrical variations in the transmission line to a minimum, especially those variations caused by changes of the physical dimensions of the transmission line itself.

(5) The greater the TDR pulse signal amplitude and the TDR receiver sensitivity, the greater the range the TDR signal will travel along a transmission line. Laboratory-type step pulse TDR units may have signal amplitude sensitivities of about 10^{-4} that of the pulse amplitude and a signal propagation range of hundreds of meters in low loss lines. The TDR unit used for these ex-

periments had a sensitivity of 10^{-2} that of the pulse amplitude and a signal propagation range of at least many tens of meters in low loss transmission lines. This unit was chosen because it was a readily available field TDR unit.

(6) The shorter the pulse length or the faster the pulse rise time of the TDR step pulse the smaller the physical length of the electrical change that can be detected in the transmission line. This factor and that of (2) are interrelated. We must have an anomaly which is electrically long compared to the pulse length in the anomaly. If this condition is not met then the amplitude of the TDR response decreases as the electrical length of the anomaly decreases. We did not vary the pulse length nor the rise time (10^{-10} sec) in the TDR equipment in these experiments.

(7) The spacing of the conductors of the transmission line should be kept small compared to the wavelength in the medium at the highest frequency in the pulse. The loss of power at the high frequencies increases as the spacing between the transmission line conductors increases. This effectively increases the TDR pulse length or the rise time on the TDR step pulse. This then affects the response discussed in (2) and (6).

Varying the spacing of the conductors of the transmission line and determining the response to anomalies was another major objective of this project. The conductor spacings were varied from 10 cm to 2 m in air. A TDR unit with an output pulse step rise time of 10^{-10} seconds was used for all our tests. The pulse had significant power at frequencies up to 3×10^9 Hz. The wavelength in air of 3×10^9 Hz is 10 cm and therefore all the measurements were carried out on transmission lines whose conductors were equal to or larger than the wavelength of the highest frequency. The increase in the step pulse rise time as the conductor spacing is increased should reflect the loss of power at the high frequencies since rise time, T_r, is inversely related to the bandwidth, BW, or the upper frequency of the pulse, in this case, by the following approximate relationship:

$$T_r = \frac{0.35}{BW}$$

Thus as the pulse rise time increases the bandwidth time decreases.

The TDR technique therefore, has the greatest resolution when the transmission line conductor spacing is very small but if the technique is to be economical for detecting leaks under a waste impoundment liner we want to have a minimum number of conductors under the liner.

The TDR technique is a versatile method for measuring high frequency electrical properties of materials in a transmission line. Many factors affect the measurements and many of the factors are interdependent. In this study we shall determine the factors that affect our application for detecting and determining the extent of leachate under a waste impoundment site. We shall determine if the technique is economical for detecting leaks under waste site liners.

We now know some of the most significant factors affecting the TDR response in materials placed in a transmission line. We also know what some of the unknowns are before the potential of the TDR technique for detecting leaks from waste impoundment liners can be evaluated. The broad objectives of this project are stated. We shall now continue by describing the experimental methods used in the laboratory to evaluate the TDR technique for detecting simulated leaks in soil. The results of the experiments will be given and conclusions made. Recommendations for further studies will also be offered.

RESULTS AND DISCUSSION

The experiments were set up to first determine how the TDR pulse rise time response varies as the conductor spacing of the transmission line increases. We next carried out experiments to determine what the physical size of the anomaly in the transmission line must be to be detected by the TDR system as the conductor spacing is varied. Finally, a series of tests were carried out to determine the change of TDR response as the position of the anomaly was moved in the transmission line.

TDR Pulse-Rise Time Versus Conductor Spacing

The rise time of a step pulse increases as the conductor spacing of the transmission line increases because the high frequency portion of the pulse gets attenuated more rapidly and thus the bandwidth of the TDR pulse decreases. The first experiment was carried out to determine the relative increase of the TDR pulse rise time as the conductor spacing of the transmission line was increased.

The TDR rise time response of the reflection from the open circuit of the transmission line was measured as the conductor spacing was increased. Figure 49 shows a number of TDR responses when the conductor spacing was 80 cm. The top trace in the upper left hand corner is of a transmission line in which the travel time of the TDR pulse is known to be 33.9 ns. This line was used to calibrate the TDR measured travel time in every case. The trace below was obtained when the TDR was connected to the transmission line. The rising and falling responses from the end of the transmission line were obtained when there was an open and short circuit at the end of the line respectively. The falling response, shown in Figure 49, immediately after the balun was obtained by short circuiting the beginning of the transmission line.

We measured the maximum rise time slope which occurred between 30 percent and 60 percent of the magnitude of the response. Figure 50 shows the relative slope of the open circuit response as the transmission line spacings were varied. The rise time of the response increases linearly as the transmission line conductor spacing increases. The rise time of the response at a conductor spacing of 40 cm is 0.2 times that of the rise time of the response when the conductor spacing is 2 m. Thus, we expect that the resolution of the system or its capability to detect small anomalies will decrease by a factor of 2 as the conductor spacing is increased by a factor of 2: in other words, the anomaly in the 2 m spacing line must be 5 times larger than the anomaly in the 40 cm spacing line to obtain an equivalent response. Absolute values are not given because there are a number of other factors that also affect the rise time of the response but these relative measurements give us a good indication of the

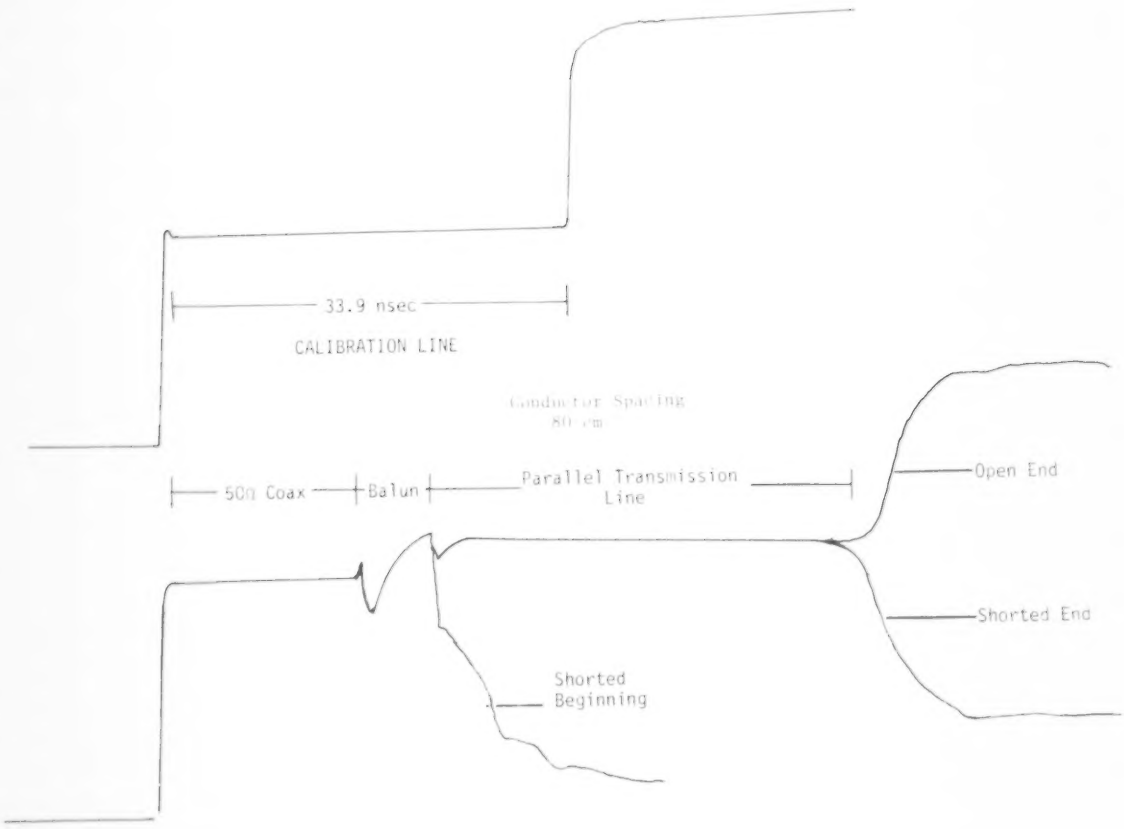


Figure 49. TDR signal responses from a transmission line whose conductor spacing is 80 cm. The trace in the upper left corner is from a calibration line in which the travel time is 33.9×10^{-9} sec.

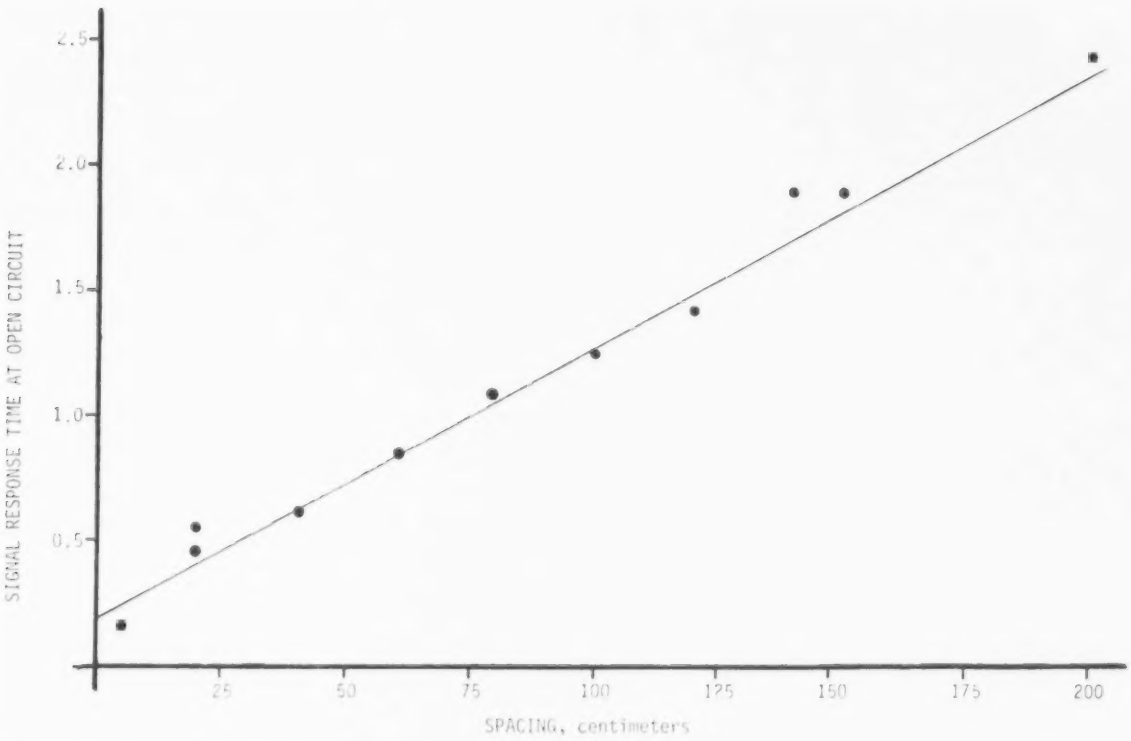


Figure 50. The relative slope of the TDR signal from an open circuit varies with the spacing between the conductors of a transmission line.

responses that we might expect on transmission with wide line spacing between the conductors in the field.

A further implication of this experiment is that as the spacing between the conductors is increased the bandwidth of the pulse will be decreased as shown earlier. If the pulse bandwidth is going to be decreased due to the attenuation along the transmission line then it would be wise to transmit a pulse with a narrower bandwidth in the first place. This means that we can increase the peak pulse power over the most useful frequencies of the TDR pulse. This will increase the length of transmission line that can be used. Further studies are necessary before we can specify the optimum TDR pulse characteristics.

Physical Size of Anomaly Versus Conductor Spacing

The next series of experiments were conducted to determine the physical dimensions of an anomaly that can be detected in a transmission line as the conductor spacing is increased. The typical conditions expected in the field were modeled using boxes of sand to simulate the leachate in the soil and air to simulate the host soil material. The modeled contrast of electrical properties was about the same as those expected in the field. Each box filled with sand was a cube with sides 15 cm long. Many boxes were placed together to increase the dimensions of the anomaly.

Length of Anomaly in a Transmission Line

The first series of experiments were to show the increase of TDR response as the length of the anomaly was increased along the length of the transmission line. The transmission line conductor spacings were set at 20, 40, 60, and 100 cm for each run. The boxes filled the space between the pipes for each run and the length of the boxes along the transmission line was varied as shown in Figure 51. Figure 52 shows four TDR responses obtained with a conductor spacing of 40 cm and the length of boxes along the line was increased from 15 cm to 90 cm.

Figure 53 shows that the TDR signal time increased in the anomaly as the number of boxes along the transmission line increased. The height of the boxes was increased from 2 to 3 boxes high and the time duration of the response increased slightly. The slight increase in response duration occurred because more of the electric field lines between the conductor passed through

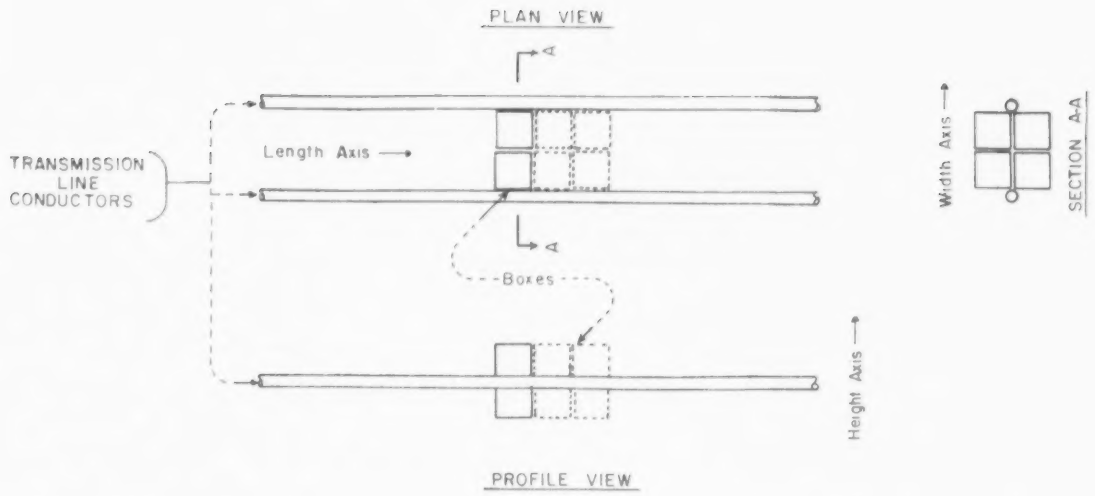


Figure 51. Plan and side view of the boxes filled with sand between a transmission line.

Figure 52. Five TDR responses from different lengths of boxes between transmission line conductors.

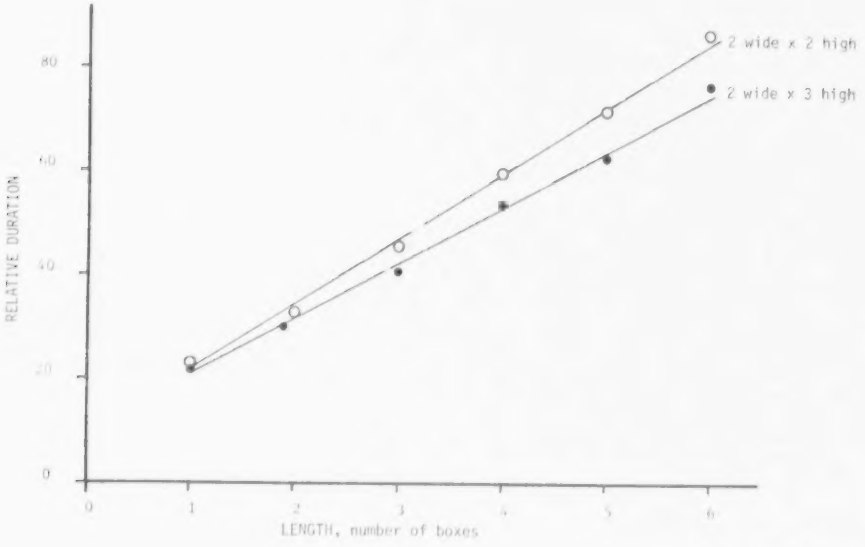


Figure 53. The TDR signal time in the anomaly increases as the number of boxes along the transmission line increases at different heights of boxes.

the sand, thus increasing the effective electric constant. A discussion of the electric field is given in the TDR review section. The TDR signal travel time in the sand was slower than in the air. In an ideal homogeneous case the travel time, t, is directly related to the length of the line in the material, L, and the dielectric constant, K, by

$$t = \frac{LK^{1/2}}{c}$$

where c is the velocity of the TDR signal in air and equal to 3×10^8 m/s.

Figure 54 shows that the amplitude of the signal response increased as the number of boxes along the length of the transmission line increased and then remained at a constant amplitude. The length of anomaly at which the amplitude stopped increasing occurred when the travel time of the pulse in the anomaly was as long or longer than the TDR pulse rise time in the anomaly.

We also note that the amplitude of the response increased slightly as the height of the boxes increased. This once again was due to the increased number of electric field lines between the conductors passing through the sand having the effect of apparently increasing the dielectric constant.

The relative amplitude of the TDR response was linear, like that shown in Figure 54 for 40 cm spacing, at all conductor spacings from 20 to 100 cm. Figure 55 shows a plot of relative signal amplitude as the length of the boxes along the transmission line relative to the transmission line spacing was varied. The curve with the solid black dots represents the case where the height of the boxes was equal to the width of the boxes in the transmission line. The curve with the circles represent the case where the height of the boxes was only one third the width of the boxes in the line. The height of the boxes only decreased the relative amplitude of the TDR response slightly. The important point to be noted from the response on Figure 56 is that the amplitude of the TDR response remained constant when the length of the anomaly was equal to or greater than the transmission line conductor spacing. The amplitude response only decreased by about 50 percent as the length of the anomaly was decreased to about one third the spacing of the conductors. This indicates that the amplitude and time duration of the response will be decreased by one third when an anomaly in the line is touching the conductors and has a height and length each equal to one third the spacing of the conductors. This is a very exciting result but we must determine the effect on the TDR response of decreasing the width of the anomaly with respect to the conductor spacing. We also must vary the position of the boxes with respect to the conductors.

Width and Position of Anomaly in a Transmission Line

In the first of this series of experiments we kept the width of the boxes equal to the spacing between the conductors of the transmission line. We then moved the center of the boxes over towards one of the conductors. The length of the boxes along the transmission line was always kept equal to the spacing between the conductors.

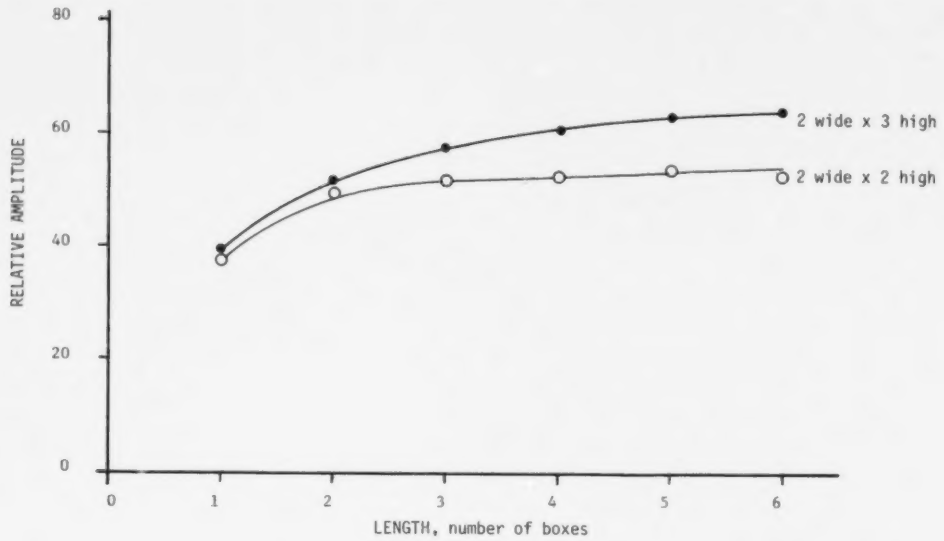


Figure 54. The amplitude of the TDR signal response varies as the length of the boxes along the transmission line varies at different heights of boxes.

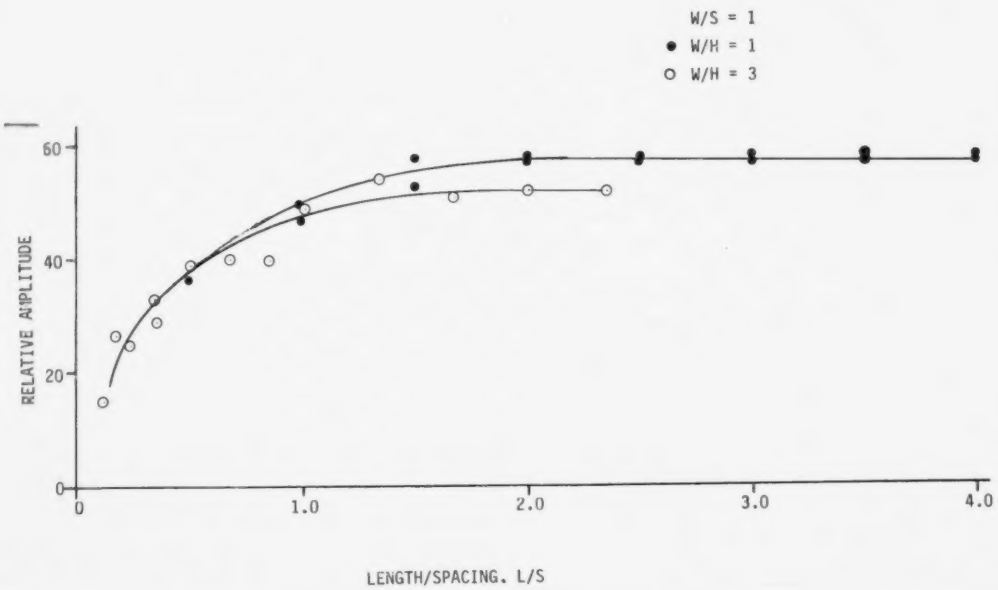


Figure 55. The amplitude of the TDR signal response varies as the length of the boxes along the line relative to the transmission line conductor spacing varies at different heights of boxes.

Figure 56 shows how the TDR signal amplitude varied as the width of the boxes relative to the conductor spacing varied. The length of the boxes along the length of the transmission line was kept equal to the spacing. The dashed curve with the •'s shows how the signal amplitude decreased as the width of the boxes decreased when the boxes were centered between the conductors. No TDR reflected signal was observed when the width of the boxes was one third the conductor spacing. The curve with the open circles, o's, shows how the signal amplitude decreased as the width of the boxes decreased but with the boxes centered about one of the conductors. We notice that the TDR signal amplitude did not decrease as rapidly when the anomaly was centered between the conductors. If the anomaly was touching both conductors then the relative response was greatest. It appears that the anomaly located about the conductor focuses the electric field lines in the line more effectively than when the anomaly was located either between the conductors and not touching either conductor.

Figure 57 shows how the TDR signal amplitude varied when the boxes had a width of one third the conductor spacing and a height equal to the conductor spacing for different lengths of boxes along the length of the transmission line and the boxes were positioned at different positions in the transmission line as shown. Once again we noticed a very significant decrease of TDR signal amplitude as the boxes were moved away from a conductor. As expected the response as the length of the anomaly along the transmission increased was very similar to that shown in Figure 55 even when the anomaly was narrower than the conductor spacing.

These experiments show us that the worst case for getting a good TDR signal response is when the anomaly lies between the transmission line conductors without actually touching either conductor. This is an important finding. The TDR can detect with sufficient signal amplitude anomalies whose sides are at least one third the spacing between the conductors of the transmission line if the anomaly is just touching or very near a conductor. If the anomaly is not touching and is not near to either conductor of the transmission line then the size of the anomaly must be increased to obtain sufficient TDR signal amplitude. Sufficient TDR signal amplitude will be obtained when the sides of the anomaly are at least one half the spacing between the conductors. Keep in mind that this result is based upon a condition where the attenuation to the signals along the transmission line are negligible. If electrical losses do exist along the line, as will be the case when the line is placed in soil under a dump site liner, then the size of the anomaly will have to be larger. Further tests are needed to determine the effect of electrical losses along a transmission line.

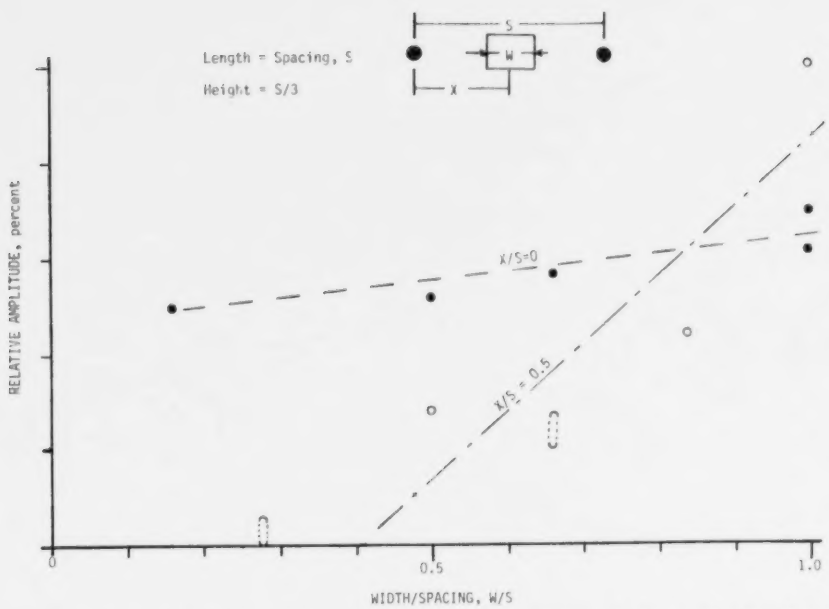


Figure 56. The TDR signal amplitude varies as the width of the boxes relative to the spacing between the conductors varies. The open circles (o) show the response when the center of the boxes are kept in the center of the conductors. The closed circles (●) show the response when the boxes are centered about a conductor.

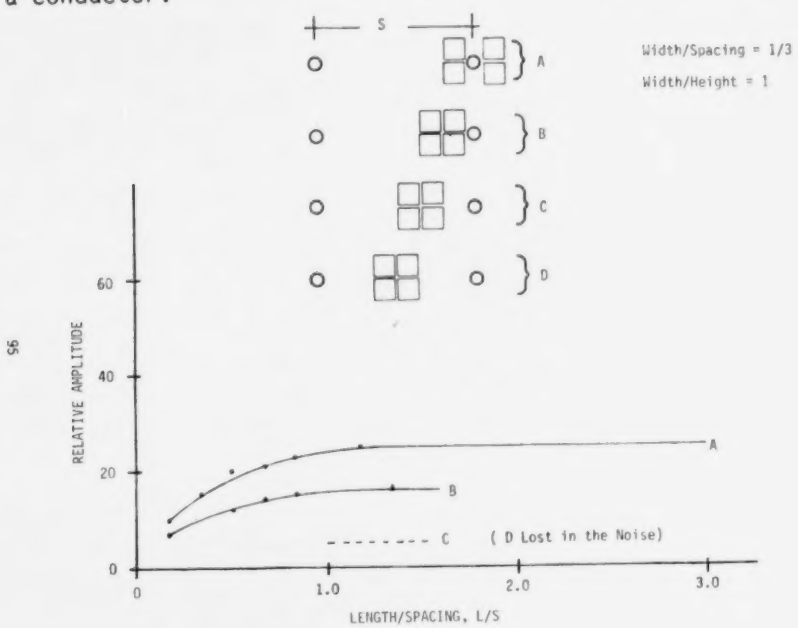


Figure 57. The TDR signal amplitude varies as the length of the boxes along the line relative to the conductor spacing varies when the boxes are at different positions in the transmission line as shown.

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